



DOCTOR OF SCIENCE (DSC)

Acoustic Interrogations Of Complex Seabeds

Guigné, Jacques Yves

Award date:
2013

Awarding institution:
University of Bath

[Link to publication](#)

Alternative formats

If you require this document in an alternative format, please contact:
openaccess@bath.ac.uk

Copyright of this thesis rests with the author. Access is subject to the above licence, if given. If no licence is specified above, original content in this thesis is licensed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC-ND 4.0) Licence (<https://creativecommons.org/licenses/by-nc-nd/4.0/>). Any third-party copyright material present remains the property of its respective owner(s) and is licensed under its existing terms.

Take down policy

If you consider content within Bath's Research Portal to be in breach of UK law, please contact: openaccess@bath.ac.uk with the details. Your claim will be investigated and, where appropriate, the item will be removed from public view as soon as possible.

ACOUSTIC INTERROGATIONS OF COMPLEX SEABEDS

Jacques Yves Guigné

A thesis submitted for the degree of Doctor of Science

Volume 1: Illustrated Description Of The Science

**University of Bath
Department of Physics
March 2013**

COPYRIGHT

Attention is drawn to the fact that copyright of this thesis rests with the author. A copy of this thesis has been supplied on condition that anyone who consults it is understood to recognize that its copyright rests with the author and that they must not copy it or use material from it except as permitted by law or with the consent of the author

Table of Contents

Abbreviations	15
Basic Introductory Glossary	15
1	17
1.1 Requirement For Accurate Assessments Of The Sub-seabed Sediments	17
1.2 Importance to Present Maritime Operations.....	18
1.3 The Technology Gap.....	19
1.4 The Value Proposition For Acoustic Coring	22
1.5 The Thesis.....	27
2	32
2.1 Capturing the Character of the Near Surface Sediments.....	32
2.2 Imaging the Fabric and Texture of the Benthic Habitat.....	32
2.3 Capturing the Essence of Roughness.....	34
2.4 The Benthic Application.....	36
2.5 Significance And Value	40
3	44
3.1 Creating a Prototype Design	44
3.2 Proof of Concept Trials.....	45
3.3 Formulating a First Answer Product.....	46
3.4 The Next Generation: The Acoustic Corer™	51
3.5 Strength Is With Coherent Summation.....	54
3.6 Introducing The JYG-Cross.....	54
3.7 Applying Data Migration Routines	56
3.8 Velocity Analysis	57
3.9 Dealing With Interference and Multiple Echo Suppression	60
3.10 Gains and Bandpass Applications.....	62
3.11 The Last Step In The JYG-Cross Processing	62
3.12 Synthetic Aperture Sonar Renderings And Processing.....	63
3.13 Low and High Frequency Chirps	63
3.14 Specifying the Size of the Receiver and Transmitter Cones	65
3.15 Processing Flow Diagram	66
3.16 Classifying the Seabed Sediments in Terms of Specular and Non-Specular	69
3.17 Anomaly Sizing.....	72
3.18 Boulder Identification.....	72
3.19 Acoustic Texture Imaging And Interpretation	77
3.20 Imaging Seafloor Features	79
3.21 Interpreting And Comparing Rendered Acoustic Data With Geotechnical Data	83
4	93
4.1 Higher Frequencies at Depth	94

4.2	Unique Configuration Spread	94
4.3	Processing of Signals Involves Beam-forming and Beam-steering.....	95
4.4	Reasons for Low Resolution Seismic Captures in Unconventional Reservoirs ..	98
4.5	High-Fidelity Of The Signals Required	100
4.6	Complementary To Existing 3D Seismic	101
4.7	What Has Been Accomplished To Date	102
4.8	First Full-scale AZ Land Pilot	104
4.9	Preliminary Results	109
4.10	Value proposition Application Directions	112
5	116
5.1	Filling in the Technology Gap.....	116
5.2	Acoustic Analysis From A Drill Stem	117
5.3	Forming a Large Wide Volumetric Acoustic Core	118
5.4	In Conclusion.....	121

Figure 1: Examples of seabed site applications that rely on thorough knowledge of the seabed character. Source: PanGeo Subsea Inc. public marketing material, 2012.	19
Figure 2: Wide-area acoustic answer product in the form of an “acoustic core” as a means to address the gap in scale for geophysical/geotechnical site investigations. Source: diagram modeled after Guigné’s PhD ASI concept 1986, released in PanGeo Subsea Inc. public marketing material, 2012.	21
Figure 3: Typical buried boulders off the East Coast of Canada of similar diameters to the standard piles used offshore. Source: PanGeo Subsea Inc. marketing archive 2010.	22
Figure 4: Typical diameter of the standard piles used offshore approaching five-meter diameters. Source: PanGeo Subsea Inc. marketing archive 2010.	23
Figure 5: Acoustic interrogations/coring with traditional geotechnical sampling and in situ testing to mitigate wind-farm seabed geotechnical related installation risks. Source: PanGeo Subsea Inc. public marketing material, 2012.).....	25
Figure 6: Acoustic interrogations/coring are complementary to seismic and traditional geotechnical sampling and in situ testing where an acoustic core is used in conjunction with CPT to replace a physical core. Source: Simmons & Company International —Information Memorandum on PanGeo Subsea Inc. March 2012.).....	26
Figure 7: X-Ray CT scan data of a horizontal core (10x10x22cm ³) showing shell pieces (yellow) and animal burrows and water pockets (red), which caused high frequency volume scattering; recovered off the coast of Venera Azzura, Italy. Source: Dr. Nicholas Pace SACLANTCEN Report SR-342 and explained in Guigné and Pace, 2007.	26
Figure 8: Sample from 0.25m ² box corer; the shrimp burrow is approx. 5cm; from the Gulf of St. Lawrence, Canada. Source: Guigné and Pace, 2007.	27
Figure 9: Dispersion test of the water column (top left) with time histories of the acoustic pulse recorded at the test site (top right). Frequency summation (bottom left). Instantaneous amplitudes for the time histories of the acoustic data recorded at test site using four different frequencies (bottom right). Source: Guigné et al., 1991.	32
Figure 10: Benthic-DRUMS hardware with electronic bottle seen in red attached to a tripod the transmitter/receiver head is seen in blue (top). The bottom figure presents an enlarged view of the transmitter head showing the four rows; the white tipped probes are the receivers. Source: Personal photographs taken in 1993.	33
Figure 11: Data acquisition occurs at each location with a sequential transmission/receive script executed in seconds for each of the forty positions with hundreds of locally distributed sounding positions taken over a region of interest, to form a sufficient database for significant statistical treatment to be considered. Source: based on author’s sketches in 2002.	34
Figure 12: An example of rescaling steps to acquire a fractal dimension from a signal. Source: Redrawn from works of Malinverno, 1990.	35
Figure 13: An example of acquiring a fractal dimension from a signal. Source: Redrawn from works of Malinverno, 1990.	36
Figure 14: Recovery of Instrument after acoustic interrogations. Source: Author’s archived photographs taken from the MV Parizeau in ocean waters over the Grand Banks, offshore Newfoundland and Labrador in 1992.	37
Figure 15: Photographic example taken of seabed as seen through the open jaws of the sampler, with acoustic grid superimposed onto the photograph to exactly show where the forty acoustic soundings occurred. Source: Author’s archived photographs taken from the MV Parizeau in ocean waters over the Grand Banks, offshore Newfoundland and Labrador in 1992.	37
Figure 16: Composite photographs of the hardware; the red electronic bottle is nestled into the framework with the its blue transducer of forty transmitting elements with receivers suspended by the cylindrical video camera, above the open jaws of the grab sampler forming the base of the instrument. Source: Author’s archived photographs taken off the vessel - MV Parizeau in ocean waters over the Grand Banks, offshore Newfoundland and Labrador in 1992.	38

Figure 17: Hilbert -transformed time histories for untrawled (A and C) and trawled (B and D) sites; highlighting comparisons in a descending five depth strata. Source: Schwinghamer et al., 1993.	39
Figure 18: Decreasing fractal values (white to yellow, red, black) plotted across the forty element sonar sliced by descending zones (where each zone represents a thickness of 1.6 cm) comparing the responses for the untrawled to the natural trawled site. Source: Modified from Schwinghamer et al.,1993 and in Guigné and Pace, 2007.	39
Figure 19: First embodiment of the ASI using sixteen sparker sources as transmitters Source: Author's archived photographs, circa 1990 from personal photo library.	44
Figure 20: Deployment of ASI in 1991 off of a pier in Newfoundland and Labrador. Source: Author's archived photographs, circa 1991.	45
Figure 21: Data acquisition geometry. Source: From Guigné et al., 1991	45
Figure 22: Processing sequence. Source: From Guigné et al., 1991 and Inkpen et al., 1991.	46
Figure 23: Beam 1 data panel. Source: From Guigné et al., 1991 and from Pike, 1998's thesis.	47
Figure 24: Beam 2 data panel. Source: From Guigné et al.,1991 and from Pike, 1998's thesis.	47
Figure 25: Beam 3 data panel. Source: From Guigné et al.,1991 and from Pike, 1998's thesis.	48
Figure 26: Beam 4 data panel. Source: From Guigné et al.,1991 and from Pike, 1998's thesis.	48
Figure 27: Depth Contours From Depth Cross-sections. Source: From Guigné et al., 1991 and from Pike, C. 1998's thesis.	49
Figure 28: Isopachyte results for six layers into the sub-seabed. Source: From Guigné et al., 1991 and from Pike, 1998's thesis.	49
Figure 29: 3D rotated presentation of the data isopachs. Source: From Guigné et al., 1991 and from Pike, 1998's thesis.	50
Figure 30: Presents a sketch and overlain bathymetry of the data acquisition configuration, the four data acquisition beams and the co-location of two boreholes and four CPT tests. Source: From Guigné et al., 1991 and from Pike, 1998's thesis.	50
Figure 31: a) Brute stack for Beam 3 showing horizon picks; b) Normal incidence trace(replicated four times) coincident with CPD10; c) Borehole 1 showing identified stratigraphy, black circles; d) Portion of log for Borehole 1. Dashed lines between a, b and c, indicate correlations between CDP horizons, normal incidence events and borehole stratigraphy. Source: From Guigné et al., 1991 and from Pike,1998's thesis.	51
Figure 32: Sonar package for the PanGeo Subsea Inc. Acoustic Corer™ Source: PanGeo Subsea Inc. marketing archive 2011	52
Figure 33: Illustration of the Acoustic Corer™ platform, opened up and sitting on the seabed. From a mechanical embodiment context, the Acoustic Corer™ is a mechanical system consisting of a tripod, two antipodal booms (arms) that rotate about the central pivot, and on each boom an independently moving instrumentation platform. Source: PanGeo Subsea Inc. marketing archive 2011	53
Figure 34: Photograph of the unit being deployed off a survey vessel in the North Sea in 2011. Source: Photo from PanGeo Subsea Inc. marketing materials, 2011.	53
Figure 35: Typical acoustic core product after the SAS rendering is completed. Source: Statoil Ormen Lange Acoustic Corer trials in the Norwegian Sea; PanGeo Subsea Inc. marketing archive 2009, reproduced by permission.	54
Figure 36: Pictorial view of the JYG-Cross configuration. Source: PanGeo Subsea Inc./ Guigné internal processing documentation; PRC-02237-1 Acoustic Corer Protocol, March 2011.	55
Figure 37: The JYG-Cross configuration in view of the Acoustic Corer™ where sweeps are generated along the red line and receivers are stationed along the green line . Source: PanGeo Subsea Inc./Guigné internal processing documentation; PRC-02237-1 Acoustic Corer Protocol, March 2011.	56

Figure 38: The line of CMP bins is shown in yellow with the acquisition lines shown in green and red. Source: PanGeo Subsea Inc./Guigné internal processing documentation; PRC-02237-1 Acoustic Corer Protocol, March 2011.	57
Figure 39: CMP trace binning. Source: PanGeo Subsea Inc./Guigné internal processing documentation; PRC-02237-1 Acoustic Corer Protocol, March 2011.....	57
Figure 40: Semblance analysis. Source: PanGeo Subsea Inc./Guigné internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.....	58
Figure 41: Constant velocity CMP gathers. Source: PanGeo Subsea Inc./Guigné /internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.	58
Figure 42: Constant velocity stacks. Source: PanGeo Subsea Inc./Guigné internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.....	59
Figure 43: Sea-surface induced multiples. Note multiples M2 and M3 are coincident. Source: PanGeo Subsea Inc./Guigné internal processing documentation; PRC-02237-1 Acoustic Corer Protocol, March 2011.....	60
Figure 44: Example of shallow water multiples. Source: PanGeo Subsea Inc./ Guigné internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.	61
Figure 45: Predictive deconvolution for suppression of multiples: (a) reflectivity, (b) impulse response, (c) trace. Traces (d)-(h) are obtained by an application of predictive deconvolution using operator length n and prediction lag α . Source: PanGeo Subsea Inc./ Guigné internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.....	61
Figure 46: AGC comparison; the profile on the left is ungained; on the right is AGCed with an 8ms operator length. Source: PanGeo Subsea Inc./Guigné internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.	62
Figure 47: Backscattered energy focusing as “seen” at Pi and Pm platform locations Source: PanGeo Subsea Inc./ Guigné internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.....	63
Figure 48: Pulse compression comparison. Source: PanGeo Subsea Inc./ Guigné internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.	64
Figure 49: Angular transducer and receiver aperture limits (i.e. ThetaR and ThetaT) Source: PanGeo Subsea Inc./Guigné internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.....	65
Figure 51: An example of the JYG-Cross multifold data. Source : PanGeo Subsea Inc. released materials, 2011.	69
Figure 52: The SIRI caisson plan view with the location of the ASI acoustic core. Source: PanGeo Subsea Inc. SIRI related permitted marketing materials, 2010 and Guigné et al., 2010	70
Figure 53: JYG-Cross processing of data where interference is present. Source: Guigné et al., 2010	70
Figure 54: JYG-Cross processed SIRI data and interpretation. Source: Guigné et al., 2010.....	71
Figure 55: SIRI SAS High Frequency rendered anomaly at a depth of approx. 4.5 m in the seabed (Panel A is a horizontal 12 m dia. plane view at that depth) and geographic plot of the different anomalies detected (Panel B). Source: Guigné et al., 2010.	71
Figure 56: Composite illustration highlighting the sizing of a boulder anomaly by calculating the x and y dimension. Source : PanGeo Subsea Inc. AC data archive, 2011.	72
Figure 57: SAS rendered plan view horizontal data imagery slice (3m x 3m section) showing the boulder target and after excavation the cluster of boulders that were grouped together. Source: PanGeo Subsea Inc. AC data archive, 2011.	73
Figure 58: Illustration exhibiting in A a vertical elevation view (10m lateral extent) where a distinct anomaly suggestive of a boulder is noted. Data panel B is the corresponding horizontal data slice (at 10 m depth). Source: PanGeo Subsea Inc. AC data archive, 2011.	74

Figure 59: Example of a horizontal section which displays isolated boulder type anomalies, and boulder/ cobble cluster signatures as imaged near the surface, with a typical boulder found proud at the site. Source: PanGeo Subsea Inc. AC data archive – Kriegers Flak, Baltic Sea, 2010.....	74
Figure 60: Example of a vertical cross-section (3m thick x 12m length) gravel / cobble layer buried at a depth of 11.0m, sandwiched between clay soil and sandy soil. Source: PanGeo Subsea Inc. AC data archive, 2011.	75
Figure 61: Example horizontal slices through the acoustic core (12 m x 12m) presenting examples of cobble sized particles, higher concentrations of gravel, and small boulders. Source: PanGeo Subsea Inc. AC data archive, 2011.	75
Figure 62: Example of two vertical slices (approximately 10 m widths, 15m depths) through rendered Acoustic Core SAS data for both the High Frequency Chirp and for the Parametric data. The CPT data shows spikes correlating to the boundaries. Source: PanGeo Subsea Inc. AC data archive, Baltic Sea site, 2011.....	76
Figure 63: High Frequency Chirp slices through the moraine. Source: PanGeo Subsea Inc. AC data archive, Baltic Sea site, 2011.....	76
Figure 64: Three High Frequency Chirp horizontal examples of boulders as detected in a clay sediment, in a sand matrix and in a sandy gravel layer. Source: PanGeo Subsea Inc. AC data archive, Norwegian fjord, 2011.	77
Figure 65: Acoustic core vertical slice example after the SAS rendering with accompanying horizontal slices. Source: StatoilHydro Ormen Lange Acoustic Corer trials in the Norwegian Sea; PanGeo Subsea Inc. marketing archive 2009, released by permission.	78
Figure 66: Acoustic core vertical slice example after the SAS rendering with accompanying interpretation and comparison to the geology of the borehole. Source: StatoilHydro Ormen Lange Acoustic Corer trials in the Norwegian Sea; PanGeo Subsea Inc. marketing archive 2009, released by permission.....	79
Figure 67: Acoustic core horizontal SAS High Frequency slices; the upper slice of debris (in red circle) and the lower slice revealing CPT rod lying on the seabed (in red circle). Source: PanGeo Subsea Inc. marketing archive, Baltic Sea site, 2010.....	80
Figure 68: Top image is a horizontal SAS High Frequency image at the seabed (12m diameter) with a clearly pronounced indentation noted near the center of the image. The lower slice presents the seafloor depression in the elevation view (depression is approximately 2m wide with a depth of 1m). Source: PanGeo Subsea Inc. marketing archive, Baltic Sea site, 2010.....	81
Figure 69: Two vertical SAS High Frequency profiles extending from where the CPT investigation aborted The resulting Acoustic Core verified that no buried acoustic anomalies were present at the site. Source: PanGeo Subsea Inc. marketing archive, Baltic Sea site, 2010.	82
Figure 70: Annotated features in a horizontal SAS High Frequency at the seabed (12m diameter). Source: PanGeo Subsea Inc. marketing archive, Baltic Sea site, 2010.	83
Figure 71: Vertical profile slices taken at two separate sites and compared to geotechnical information. Both sites display good agreement between the CPT data and the acoustic cores, with the acoustic data displaying more events than are visible in the CPT data. Source: PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011.....	85
Figure 72: Vertical profile slice comparing to geotechnical CPT information. A major discrepancy exists at event A. Source: PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011.....	86
Figure 73: Vertical profile slice comparing the acoustic interpretation, borehole and geotechnical information, displaying with inserted letters the different types of laterally varying stratigraphy that cannot be spatially mapped by the CPT or borehole data alone. Source: PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011.....	87
Figure 74: Typical conventional sub-bottom profile with associated CPT response; noticed the smeared masking character in the record caused by the presence of gas in the sediment. Source: PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011	88

Figure 75: Two associated horizontal slices for the SAS rendered High Frequency Chirp and for the Parametric Data, highlighting the spread of the gas layer. Source: PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011.....	88
Figure 76: Two vertical SAS profiles for the High Frequency Chirp and for the Parametric Data, highlighting a gas layer. Source: PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011.....	89
Figure 77: Descriptive Analysis. Source: Based on the data exhibited in the Anholt study, PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011.....	90
Figure 78: Total Number Of Anomalies by diameter. Source: Based on the data exhibited in the Anholt study. Source: Based on the data exhibited in the Anholt study, PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011.....	90
Figure 79: Total Number Of Anomalies by Burial Depth. Source: Based on the data exhibited in the Anholt study, PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011	91
Figure 81: Conceptual drawing of the beam-forming and steering deep into the earth. Source: Personal conceptual drawing for Acoustic Zoom Inc., November 2012	93
Figure 82: Pictorial of a typical receiver array configuration. Source: Personal conceptual sketch, 2007	95
Figure 83: Pictorial of wide angle steering with an array smaller in size. Source: Personal conceptual sketch, 2007	96
Figure 84: Graphic presentation of the transmission and reflective approaches. Source: Acoustic Zoom Inc. in-house explanatory drawings, 2011	97
Figure 85: Graphic presentation of the beam formation (top); the bottom pictorially presents a simulation of the 0.5° resulting narrow beam width at -3 dB with side lobes 15 dB below the main beam for the AZ 120 wavelength based array for 16 radial spokes. In theory, AZ beam-forming results should provide for an additional 36 dB gain, over the incoherent ambient noise. Source: Acoustic Zoom Inc. in-house explanatory drawings, 2011.....	98
Figure 86: Graphic presentation of the diffuse scattered data collection. Source: Acoustic Zoom Inc. in-house explanatory drawings, 2011	99
Figure 87: Graphic presentation that compares the AZ angular image approach against typical conventional seismic. Source: Acoustic Zoom Inc. in-house explanatory drawings, 2011.....	100
Figure 88: AZ beam focusing principle for normal and angle impinging wavefronts, illustrated via emission and reciprocity principle. Source: Acoustic Zoom Inc. in-house explanatory drawings, 2011	101
Figure 89: High frequency source testing at the ExxonMobil Friendswood Experimental test site in Houston, Texas. Source: Pangeo Subsea Inc. internal interim report to ACOA – AIF research project and to NRC- IRAP project, 2010	103
Figure 90: J.Y. Guigné and A. Gogacz at the ExxonMobil Friendswood Experimental test site in Houston, Texas. Source: ACOA –AIF and NRC-IRAP Interim Reports, 2010.....	103
Figure 91: Photograph relates to vibrating plate of the vibroseis truck, which was modified to generate stable higher frequencies, and the pads under the plate of the truck, to better couple the vibrations to the earth. Source: ACOA –AIF and NRC-IRAP Interim Reports, 2010	104
Figure 92: Field county land plot for first full scale AZ pilot in the region of San Antonio, Texas. A 12.5 sq. km area was AZ imaged in November 2011. Source: Global Geophysical Services Inc. field photograph (released to Acoustic Zoom Inc. with permission) with AZ receiver footprint, 2011.	105
Figure 93: Layout script used to distribute the 4000 receivers with specific spacing as per the 120 wavelengths at associated frequencies of up to 200 Hz. Source: Acoustic Zoom Inc. in-house field preparation notes, 2011	105
Figure 94: First full scale AZ pilot in the region of San Antonio, Texas. A 12.5 sq. km area was imaged as part of Global Geophysical Services' Wrangler 3D multi-client survey in Wilson County Texas in November 2011. In the picture: C. Clements, J.Y. Guigné, and A. Gogacz stand at the	

apex of the AZ receiver star array. Source: Acoustic Zoom Inc. in-house field photographs, 2011	106
Figure 95: Terrain on which the geophones (in orange) were implanted in the region of San Antonio, Texas. Source: Acoustic Zoom Inc. in-house AZ first pilot field photographs, 2011	106
Figure 96: Vibroseis truck placement with 5 source locations, 4 sources on the $\frac{1}{4}$ wavelength perimeter and 1 source at or near the centre of the receiver array. Source: Acoustic Zoom Inc. in-house AZ first pilot field placement sketch, 2011.....	107
Figure 97: Vibroseis truck placed in the excavated cross. The loose brown clay was removed to reveal a concrete hard red clay basement. Source: Acoustic Zoom Inc. in-house AZ first pilot field photographs, 2011	107
Figure 98: Data Acquisition Van. Source: Acoustic Zoom Inc. in-house AZ first pilot field photographs, 2011	108
Figure 99: Data acquisition truck and signal quality operations. Source: Acoustic Zoom Inc. in-house AZ first pilot field photographs, 2011.....	108
Figure 100: Final sensor location plot. Source: Acoustic Zoom Inc. in-house AZ first pilot, sensor field location printout, 2011	109
Figure 101: Final sweep definition: 170 Hz, 2 dB/octave pre-correlation slope, 40 seconds duration with a 50% drive-level. The frequency plot is at the Eagle Ford formation. Source: Acoustic Zoom Inc. in-house AZ first pilot, sensor field location printout, 2011.....	110
Figure 102: Actual conventional seismic sweep at the Eagle Ford formation where the pilot took place with a definition of 6-96 hz, 1 dB/octave pre-correlation slope, 24 seconds duration and a resultant max 70 Hz typical frequency sweep peak. Source: Global Geophysical Services internal data plot, 2011	110
Figure 103: Vertical stacking folds of 1, 200, 300, 400, 512, for two of the five vibroseis locations Source: Acoustic Zoom Inc. in-house AZ first pilot preliminary analysis plots, 2012	111
Figure 104: First look at azimuthal frequency distribution at 1.5 second two way travel time, with frequency parameterized along radial lines, heading of each acquisition line represented angularly and each radial line represented by distinctly colored sector. Source: Acoustic Zoom Inc. in-house AZ first pilot preliminary analysis plots, 2012.....	112
Figure 105: Applications are from exploration to production. Source: Simmons & Company International; Information Memorandum on PanGeo Subsea Inc. February, 2010.	113
Figure 106: Acoustic Zoom imaging and subsurface characterization pictorial. Source: Acoustic Zoom Inc. in-house AZ value proposition diagram, 2012	114
Figure 107: Application of an ASI by removing the tripod legs and replacing this by a drill stem. The drawing is in support of the patent called "Wide Area Seabed Analysis" by J.Y. Guigné; with the original drawing depicting a pictorial rendering of the acoustics operating like PanGeo Subsea Inc's Acoustic Corer. Source: personal original sketch as produced for the patent, 2007.....	118
Figure 108: Application of a large volumetric mapping ASI which would rely on a "bottom crawling" vehicle or other remote ROV system typically used in offshore related work. The drawing is in support of the patent "Discrete Volumetric Sonar Method And Apparatus" by J.Y.Guigné, G.Dinn, A.Gogacz and N.G.Pace. Source: personal original sketch, drafted and produced by PanGeo Subsea in support of this new patent concept, 2012	119
Figure 109: Application of a large volumetric mapping ASI which would rely on a bottom crawling vehicle or other ROV. The drawing is in support of the patent "Discrete Volumetric Sonar Method And Apparatus" by J.Y.Guigné, G.Dinn, A.Gogacz and N.G.Pace. Source: personal original sketch, drafted and produced by PanGeo Subsea in support of this new patent concept, 2012	120
Figure 110: Application of an ASI through the creation of SAS cells stitched together precisely in checkerboard acquisition. The drawing is in support of the Discrete Volumetric Sonar Method And Apparatus patent by J.Y.Guigné, G.Dinn, A.Gogacz and N.G.Pace. Source: personal original sketch, drafted by PanGeo Subsea in support of the patent concept, 2012.....	120

Acknowledgements

When one writes a PhD thesis it soon becomes a very personal objective, primarily of pursuing original research and ideas. Writing a DSc thesis is different. It is a journey that typically spans decades; it tends to be all encompassing and by its very nature engulfs family members and colleagues. Hence, this acknowledgement note is a chance to say a heartfelt thanks; it allows me to indicate by name the individuals that contributed so much to the work that forms the context of this thesis. It also allows me to highlight the depth and magnitude of the research and those who journeyed with me along this road of discovery and invention.

The thesis is first dedicated to Anna, my dear wife, who lived through the many trials, failures, and triumphs associated with my research. She has seen the various incarnations of the ideas that now form this DSc thesis come together over more than twenty years of experimentation, design, and application. She truly deserves the highest form of recognition for her unfailing belief in my work and for her sense of humour during times of great trials and difficulties. The dedication is also given to Françoise and Simone, my two daughters. They were very young when my PhD thesis was examined in Bath, but they lived through the years that followed and were an integral part of my scientific pursuits. They remain inspirational, and this Doctor of Science initiative is a shared experience with them. Andre Pant and Robert Bruce Lilly, their husbands, have now also stepped into this journey, offering constant encouragement, as well as well-needed teasing and a helping hand. I have been so fortunate to have Jeanne Guigné, my mother, and Margaret Kearney, my mother-in-law, close by to share the excitement of participating in such frontier work. It is because of family that such a thesis is enjoyable to write.

It is often said that a supervisor could make or break a student's chance to succeed. I am fortunate to have had Professor Nicholas Pace of Bath not only guide me through my PhD but also to have had him follow the work and ideas in the years that followed. Nicholas is a rare and highly regarded scholar in his own right—truly a Professor's Professor. The development and shaping of the acoustic interrogation concept as conceived in the early PhD years in Bath has led both of us to mature and test the imaging ideas on near surface sediments to the depths of the earth. Of equal importance is a big thanks to Françoise Pace who, with dutiful patience, has seen me over the years descend onto their home. She prepared many dinners and endured the many walks along the Bath canal listening to the nonstop physics chatter between Nick and me.

Special thanks must also be given to my colleagues at the University of Bath—in particular to Dr. Philippe Blondel and Professor Jonathan Knight—for their encouragement. Philippe has given structural thesis advice and supported the scientific collection of papers and patents for review.

In research and development work that spans at least two decades, there have been many colleagues who have passed through various implementation stages. They have made a direct mark on my understanding and scientific approaches. I wish to acknowledge the influences of what I would consider first amongst “friends and giants” in the field. Dr. Jack Clark immediately appreciated the impact the Acoustic Sub-seabed Interrogator (ASI) could have on marine geotechnical practices in Canada and pushed me firmly to “get on with” developing it for future Arctic offshore applications, which today we are ready to do. Likewise, Dr. Peter Schwinghamer understood what I was attempting in introducing an application of chaos and geo-statistics as a means of delivering a measure of benthic habitat health. I learnt much from his deep understanding of marine

ecological systems. Likewise Dr. James Wright entered just when I needed a scholarly voice to further explain and differentiate the physics behind the Acoustic Zoom methodology against traditional seismic practices. These three friends are dearly missed, but their teachings continue to resonate with me.

Mr. Gunnar Rasmussen taught me about sound and vibration instrumentation and in particular exotic transducer designs; Dr. Frank Schowengerdt provided a depth and knowledge on experimental physics. Both colleagues' encouragement led to the push to get the science ideas out commercially into useful and valued products.

In all journeys where an idea eventually shapes itself into a recognized service, one crosses over into the industrial application sector, where technical developments can take place; financial support and management are essential for such success to occur. I wish to fully acknowledge the business, engineering, and scientific partnerships that I have within PanGeo Subsea Inc. and in Acoustic Zoom Inc. First, I am lucky to be a co-founder with Ms. Moya Cahill; together we created PanGeo Subsea, a business that focused on commercializing and implementing the ASI concept for delivering "acoustic cores." She is the one that stepped up in 2005, recognized the merit of the science, and committed to seeing it be adopted offshore. Together we shaped a dedicated development team and pursued the financial venture funds required. Second, I have enjoyed working with Mr. Neil Philips, our financial comptroller for over fifteen years, and he has proven to be a true friend and supporter, always finding a financial solution when funds were needed. The third and equally important pillar in executing the ASI designs, the engineering developments, and the operations is Mr. Gary Dinn. Together we have taken on the challenges involved in innovating new sonar platforms and in shaping what today is PanGeo's Acoustic Corer technologies. The trust that Gary has provided me in accepting the science directions that I have been dogmatically pursuing and his "roll-up-the-sleeves" participation has directly helped shape the variances in designs that make the product commercially acceptable.

In projects of this magnitude and complexity, the work plans are undertaken through dedicated teams of highly talented individuals. I cannot begin to express my thanks to all the scientists and engineers involved in the various phases of the designs and developments and experiments. However, I wish to single out the following colleagues who at various stages participated closely with me in advancing the concept. Taking ideas into working prototypes then leaping forth into delivering on commercial products is not for the faint of heart. Starting from a historical lineage, they are as follows: Dr. Chris Pike, Steve Inkpen, Jerry English, Peter Hunt, Dr. Ian McDermott, Tom McKeever, Mel Hicks, Dave Hicks, Dr. Sam Bromley, Dr. Richard Charron, Dawn Ryan, Adam Gogacz, Dr. Clyde Clements, Ryan Laidley, Bill Hunt, Allison Brown, Dr. James Stacey, and Andre Pant. I also wish to mention Tom Fleure of Global Geophysical Services, who has been providing seismic-geophysical technical support and the first full scale Acoustic Zoom pilot opportunity. A true partnership exists between us as we tackle the Acoustic Zoom ideas and science. The exchanges with Jon Machin of Geomarine Inc. on the directions and arguments for pursuing geostatistics involving the ASI approach for offshore wind farm site investigations are most invigorating, as his vision crosses closely with what I believe to be the future of marine geotechnical engineering. His exchanges have helped to formulate a better appreciation of the value proposition needed to meet offshore wind farm seabed requirements.

As one can appreciate, innovation involves high financial risks. I am particularly grateful for the long-term, patient support shown by the following financial advisors/sponsors of the work: Leif André Skare, Greg Herrera, and Jim Sledzik of Energy Ventures, Dr. Trevor Burgess of Lime Rock Partners, and Dr. Don Riley of Chevron Ventures. Dave Bailey (who recently passed away) and Carl King of the National Research Council (NRC),

managers of the IRAP program, were first sponsors of the PhD study and later continued to underpin the development of the acoustic science protocols.

Finally, it should be noted that Karen McDonald and Robert Bruce Lilly were instrumental in collating the publications and patents for the thesis volumes and helped to format the document as per the University of Bath guidelines.

Preface

The implementation of the Acoustic Sub-seabed Interrogator (ASI)—from its initial experimental concept research phase, which the author pursued at the University of Bath in the form of his PhD thesis (early 1980s), through to full-scale prototyping (late 1980s, early 1990s) and finally to commercialization (mid-1990s onward)—has had the underpinning support and funding of major granting agencies and industrial sponsors/investors. The present work, which forms the content of this Doctor of Science thesis, is the manifestation of over twenty-five years of research and development costing tens of millions of dollars. Therefore, I wish to mention the sponsorship of the agencies, granting institutions, and investors who backed the concept from its early formation stage and pursued the engineering developments leading to today's commercial market acceptance and utilization.

From 1982 to 1986, the National Research Council of Canada (NRC), under an Industrial Research Application Program (IRAP), supported this University of Bath PhD research project. This led to the support of major research granting agencies, Oil & Gas industrial sponsorships, and research centres to help back the development of a scientific prototype and trials in 1990 and continuing on to 1995. This early development of the ASI was made possible by the Centre for Cold Ocean Resources Engineering (C-CORE), the Natural Sciences and Engineering Research Council of Canada (NSERC), the Atlantic Canada Opportunities Agency (ACOA), the Atlantic Geoscience Centre, and the NRC Institute for Marine Dynamics (now the Institute of Ocean Technology [IOT]). The industrial sector was instrumental in providing major operational funds for sea trials around the world; the first sponsors were Mobil Oil Canada Limited, Gulf Canada Resources Limited, Petro-Canada Resources Limited, and Esso Resources Canada Limited.

From 1995 to 2005, various research grants by NSERC and NRC-IRAP were issued to Guigné to conduct scientific laboratory and near-shore studies into the physics of the ASI's acoustics as it applied to imaging the seabed. This was complemented with major contracts by the Canadian Department of Fisheries and Oceans under their Northern Cod Science Program. The acoustic work related to quantifying the effects of otter trawling on benthic habitats. This work was supplemented by the financial support of the National Water Research Institute (NWRI) for investigations into the use of broadband acoustics for mapping subtle discontinuous lakebed features.

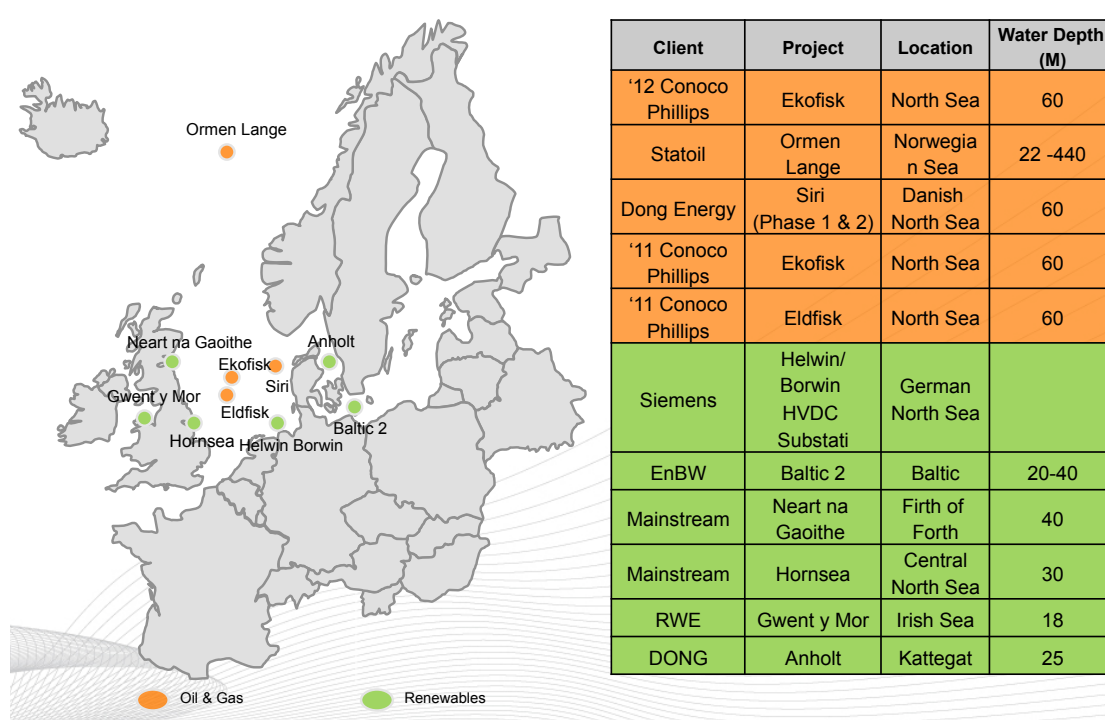
The commercial development of the ASI was first considered in 2004 and 2005 with angel funding by Pan Maritime Energy Services Ltd to explore the ASI's value proposition for the Oil & Gas offshore developments. This led to the creation of PanGeo Subsea Inc. in 2006, of which Ms. Moya Cahill (of Pan Maritime Energy Services Ltd) and Dr. Jacques Yves Guigné (of Guigné International Ltd) were the original founding partners. Energy Ventures Inc. of Norway invested \$9M (USD) in 2006 for the engineering and offshore testing of a prototype ASI called "Acoustic Corer." This was followed by a further investment in 2009 of \$11M (USD) by Lime Rock Partners and Chevron Technology Ventures for the building and commercializing of the ASI technology and its ROV mounted sub-bottom imager (called SBI) and for its associated answer products and geophysical processes, aimed for worldwide marketplace utilizations.

NRC, through their IRAP research grants, continues to provide support (from 2006 to present) to refine the acoustic protocols and to explore new concepts such as the Acoustic Zoom (AZ) initiative. In 2010, a major two-year \$750,000 (USD) contribution grant was issued by ACOA's Atlantic Innovation Fund (AIF) to help sponsor the research of the Acoustic Zoom method through to its first pilot. In 2011, Global Geophysical

Services Inc. provided approximately \$1.9M (USD) in field pilot logistics and an investment of a further \$1M (USD) dollars to pioneer the processing protocols.

In 2012, the Petroleum Research Newfoundland & Labrador (PRNL) agency and its industrial partners, Statoil, Husky Energy, Suncor Energy and Chevron, provided \$500,000 for the design and engineering delivery of a working resonant-based marine seismic source for an eventual marine AZ pilot.

Since 2010, eleven offshore commercial contracts worth more then \$15M (USD) have been serviced by PanGeo Subsea Inc. for the ASI based data acquisition, processing and delivery of its highly valued answer products and interpretative results. The graphic below presents a synthesis of the Acoustic Corer's commercial work up to and including January 2013.



An example of the adoption and distribution of commercial work that PanGeo Subsea Inc. undertook since 2010 utilizing its Acoustic Corer. Source: PanGeo Subsea Inc. marketing material, 2013.

Definitions on Acronyms and Abbreviations

Abbreviations

AC	Acoustic Corer™, commercial adaptation of Guigné's ASI concept
ASI	Acoustic Sub-seabed Interrogation, scientific methodology name
AZ	Acoustic Zoom® scientific methodology name for seismic method
CPT	Cone Penetration Test
HF	High Frequency
LF	Low Frequency
LFM	Linear Frequency Modulated
P-wave	Compression wave
ROV	Remotely Operated Vehicle
SAS	Synthetic Aperture Sonar
UNCLOS	United Nations Committee

Basic Introductory Glossary

Acoustic Core: the product of ASI data acquisition and processing in which a rendered image of the sub-seabed is produced.

Acoustic Corer™ (AC): a high-definition commercial acoustic sub-bottom imaging system that produces an acoustic core within which buried objects with target strength equivalent to boulders extending beyond 0.5 meter diameter are identified and mapped. The Acoustic Corer™ technology can be divided into three major systems: Subsea System; Topsides Equipment; and System Software.

Acoustic Zoom® (AZ): AZ is a novel seismic exploration / exploitation technique adapted from the ASI's stationary, beam-forming interrogating protocols which holds potential for high resolution imaging of geological structures. This is achieved by using deep-penetrating beam-formed and beam-steered seismic signals.

Benthic-DRUMS: acoustic sampling tool designed by Guigné to provide a three-dimensional acoustic snapshot of biogenic activity within surficial sediments to a depth of 15 to 20 centimetres below the seafloor. The Benthic-DRUMS's design encompassed four rows of ten independent, broadband parametric array based transmitters to deliver pencil beam signals of high frequencies into the seabed. Matching receivers were co-located to the transmitters

Boulder: as defined by The British Standard (BS1377:1975), a rock fragment with grain size greater 200 mm. The American Standard (USA ASTM D422) defines a boulder as a rock fragment that has a grain size greater than 256 mm.

Chirp sonar: an acoustic sub-bottom profiling system that utilizes a signal in which the frequency increases ("up-chirp") or decreases ("down-chirp") with time.

Cobble: as defined by The British Standard (BS1377:1975) a rock fragment that has a grain size greater than 60 mm and less than 200 mm. The American Standard (USA ASTM D422) defines a cobble as a rock fragment that has a grain size greater than 76.2 mm and less than 256 mm.

Cross-section: images taken vertically down the acoustic core, which shows the acoustic intensity variation in the x or y plane with depth.

Gravel: as defined by The British Standard (BS1377:1975), a rock fragment that has a grain size greater than 2 mm and less than 60 mm. The American Standard (USA ASTM D422) defines gravel as a rock fragment that has a grain size greater than 4.75 mm and less than 76.2 mm.

Fractals: a series of irregular and fragmented patterns

JYG-Cross: a seismic reflection technique consisting of a multiplicity of transmitter and receiver positions in which data is collected at varying offsets along two roughly orthogonal lines. The resulting “shot gathers” are then processed using mostly conventional seismic processing. This technique enhances coherent reflections from stratigraphic layers by exploiting the multiplicity of data through stacking to enhance coherent events and cancel out noise. This method in the ASI’s data acquisition is akin to traditional seismic reflection techniques.

Parametric Sonar: a sonar that transmits two signals of slightly different high frequencies at high sound pressures (primary frequencies). Because of non-linearity in the sound propagation at high pressures, these primary signals interact and a secondary frequency (difference of the transmitted frequencies) is generated. This “secondary” is low frequency, has large bandwidth and narrow beam and is capable of deep penetration into the sub-seabed.

Slice: images taken horizontally across the acoustic core at any given depth. They represent a downward, 2-D data profile of the acoustic core.

Synthetic Aperture Sonar (SAS): an acoustic acquisition technique that generates the effect of a large transmit-receive aperture by signal processing means rather than by actual use of a large array. The large (virtual) array is synthesized through the motion of a small array over a large area relative to the target.

ARGUMENTS FOR ACOUSTIC INTERROGATIONS OF THE SEABED

1.1 Requirement for Accurate Assessments of the Sub-seabed Sediments

As required for the design of specific offshore installations, the physical and behavioural properties of the soil in those places have been provided by offshore site investigations. Over the past several decades, a phased approach to site investigations has emerged to better evaluate the inherent variability of natural sediments¹. However, cost and complexity of field programs have also increased because of the need to acquire an accurate 3-dimensional qualitative and quantitative picture of the subsurface (Dowse, 1986; Stuyts et al., 2011). The ability to develop offshore resources in a safe and cost-effective manner is predicated on the accuracy of the acquired seabed information; significant losses can result if the information is faulty.

Case histories and review papers on site investigations in the North Sea and the Beaufort Sea indicate that typical borehole and cone penetration test (CPT) densities range from 11,250 m² to 112,000 m² (de Ruiter et al., 1975; Semple & Rigden, 1983; Ruffell et al., 1985). Jardine et al. (2005) also describes the type of comprehensive pile designs that influence the costs. The actual soil volumes used for these measurements are small, and interpolation between test sites is often inaccurate (Stuyts et al., 2011). Detailed geophysical mapping between test sites, as typified by the 10–50 m grid of North Sea surveys (see Semple & Rigden, 1983; Ruffell et al., 1985; de Ruiter et al., 1975), has proven in present day work to be generally successful for a first examination of the broad horizontal uniformity of soils but limited in dealing with near surface sub-seabed geo-hazards (DONG Energy executives in exchanges with PanGeo Subsea, 2011).

It is well appreciated that onshore geophysical surveying has many sensing techniques to use in delineating the distribution of soil conditions, including electrical, magnetic, gravity, electromagnetic (radar), and seismic methods. Owing to the properties of the water column, marine geophysical methods are primarily seismic and acoustic. Other geophysical techniques are used to a lesser extent. The differentiation between acoustic and seismic is not well defined, and the term *acoustic* generally refers to devices that transmit energy into the sea floor at frequencies ranging from one (e.g. Telford et al., 1990) to hundreds of kiloHertz (e.g. Lurton, 2004). In the offshore, acoustic systems are generally towed or supported on remotely operated vehicles (ROV) rather than employed in a fixed mode.

The primary strength of such towed or propelled systems is their ability to map the continuity of interface reflectors on a continuous basis. The term *interface reflector* refers to boundaries between materials with dissimilar acoustic transmission properties. These boundaries are often lithological in nature and can be caused by changes in sediment type or properties (e.g., bulk density).

It has been well noted in the literature that under certain conditions acoustic reflectors do not correlate well with boundaries identified by geotechnical tests (Mayer, 1979; Mayer & LeBlanc, 1983; Guigné, 1986). This situation can be caused by interactions between the outgoing acoustic pulse and the soil stratigraphy or by soils characterized by a high degree of inhomogeneity (e.g., glacial tills or boulder lags). These conditions give

¹ This section is paraphrased from Clark and Guigné's 1988 journal paper, which evolved out of Guigné's 1986 thesis on the "Acoustic Sub-seabed Interrogator" concept. This journal paper was written to introduce the status in 1988 of marine geotechnical engineering practices and of offshore site investigation issues, when dealing with complex glaciated offshore regions

anomalous reflections and distorted or masked stratigraphic profiles. Geotechnical research is directed to extract meaningful information from these data.

Difficulties also exist in knowing what constitutes reality or the “ground truth.” For example, despite a test density of about 1 borehole or CPT every 800 m² in the North Sea Forties field, pile driving revealed significant variations in soil properties that were not predicted by the borings (de Ruiter et al., 1975). The unexpected variations were apparently influenced by the assumption that anomalous strength data in a weak zone were due to sample disturbance. In situ tests, while providing some relief from the problems of sample disturbance, may be affected by fabric related discontinuities on a scale larger than that affected by the test procedure (Marsland, 1985).

Data sets acquired by engineers and geophysicists generally involve empirical correlations that are tenuous. The real question to be answered then is what measurement could constitute the ground truth for engineering applications. Confusion still exists about the relationship between data produced by seismic/acoustic profilers, by various in situ probes, and by the laboratory methods that provide the real properties of the soil (i.e., ground truth).

Effective correlation between data sets is therefore not automatic; quantitative results are directly tied to the level of calibration of the instruments and tests used. The basis for agreement between interpretations of acoustic and penetrometer data is achievable provided the lateral extent and variability of sediment types are known and accounted for when planning the placements of the in situ cone tests.

As mentioned previously, there are limitations to the use of acoustical surveying tools and techniques in terms of their ability to provide meaningful information to the marine geotechnical engineer. Research in digital signal processing, in the technology of multi-beam, broadband, and Synthetic Aperture Sonar profiling devices, and in acoustical applications of very-high-speed parallel-processing graphic-based computer data processing architectures are providing geotechnical engineers with better data management tools for measuring and understanding the geo-acoustic behavior of the seabed materials.

1.2 Importance to Present Maritime Operations

For the past thirty years, seabed site investigations have evolved into strategic economic and safety risk mitigation activities for maritime related engineering projects. There is a requirement by Marine Geotechnical Engineers for detailed and accurate 3-dimensional assessments of seabed sediment types, their conditions, and their character in order to mitigate risks for offshore foundation and infrastructure installations, which interact in some form with the seabed. Figure 1 presents typical and current offshore engineering activities that rely heavily on reliable geotechnical seabed information.

The renewable energy sector is rapidly expanding its wind farms to the offshore and hence it is critical to have confident geotechnical knowledge of the sediment conditions that would shape the stability of wind farm foundations. This is equally true for the oil and gas sector, especially as deep ocean operations are expanding. There is also a recent push for seismic exploring and ocean mining of sulphides and gas hydrates (e.g. Hart et al., 2011; Avery 2011), which will require high definition, wide-area marine geotechnical investigations beyond current practices and resolution scales, to enhance the effectiveness of their mining operations. There is growing awareness and debate related to accessing Arctic resources safely and reliably (see Kullerud et al., 2013 referring to UNCLOS article 76) and site investigations are moving to the foreground of defining these resources.

Traditionally, such seabed survey demands were focused on shallow water mine countermeasures for the Navies. The study of underwater acoustics, driven primarily by defense requirements, evolved in importance and expanded to provide attempts at classifying sediment types and targets primarily from various backscatter relationships (e.g. Greenlaw et al., 2004)

To seize meaning from the correlations, these relationships rely on prior knowledge of the extent of variability in soil properties that exists.

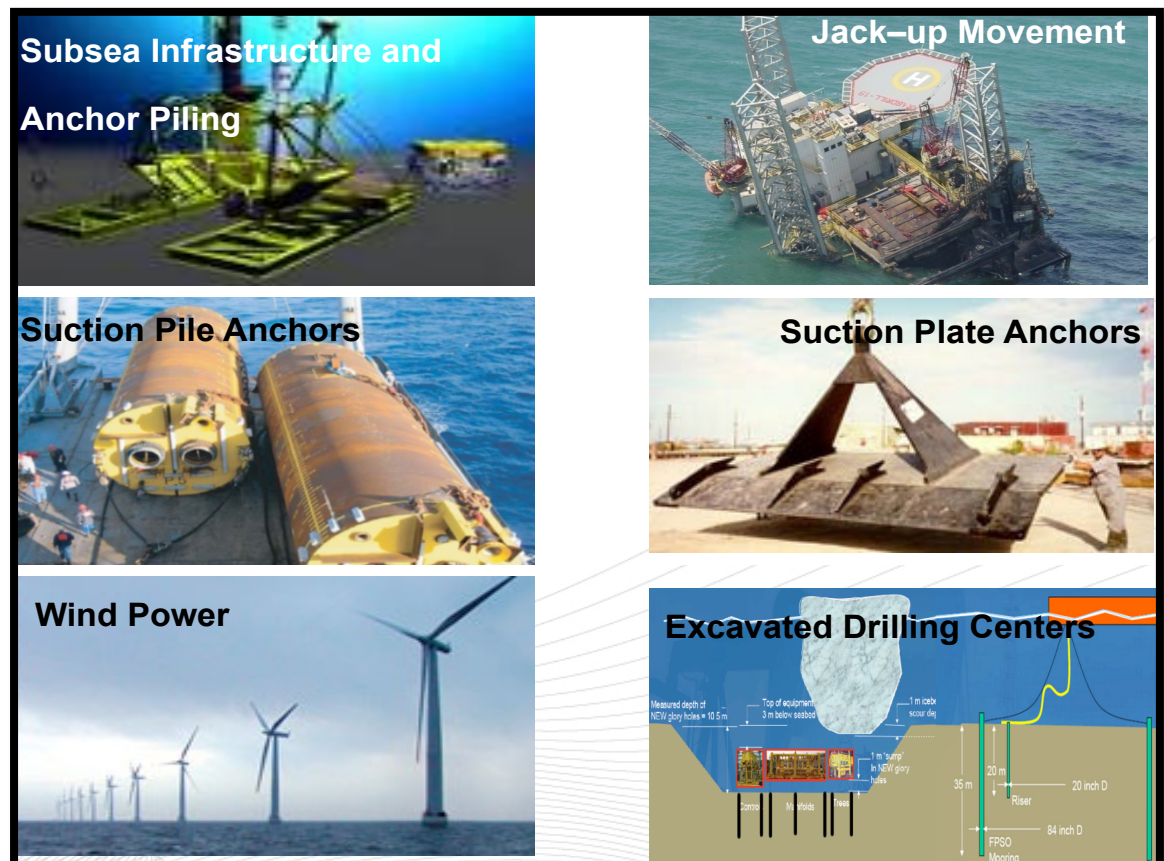


Figure 1: Examples of seabed site applications that rely on thorough knowledge of the seabed character. Source: PanGeo Subsea Inc. public marketing material, 2012.

1.3 The Technology Gap

In recent years, marine geotechnical site investigations for offshore foundations, for dredging operations of harbours and channels, and for sub-seabed installations have had to place new demands on acquiring more reliable knowledge on the composition of the seabed to address in a cost effective manner the issues of buried geo-hazards, sediment property discontinuities, or trapped pollutants being released into the water during excavation operations.

Physical coring and geotechnical sampling, whilst generally considered to be the definition of ground truth, are limited by spatial sample size. These spot investigations are often limited in delivering meaningful statistics as their footprints are simply too small unless clusters of sampling have been undertaken. This is especially true when mapping inhomogeneous seabed regions, which pose great variance in their composition. Diver-assisted sediment sampling and remote camera and/or video observations typically provide a similarly limited one-dimensional view.

Sub-bottom acoustic vertical incidence echo sounders have played an important role in exhibiting 2-dimensional acoustic bottom maps; fundamentals in applying underwater acoustics are well explained in the literature (Kinsler et al., 2000; Papadakis, 2000; Lurton, 2002; Waite 2002; Hovem, 2007). Seabed acoustics rely on the reflectivity properties of the sediment to provide rough estimates of seabed boundaries, texture, and grain size. However, uncertainties exist when imaging discontinuous bottom types, as the strength of these mapping methods are founded on capturing the continuity of reflecting sub-seabed internal boundaries. These mapping methods dramatically fail when the returning acoustic signals are backscattered and variably attenuated. Acoustic imaging and classifications of seabed types nevertheless hold great promise, especially with the advent of recent digital signal processing tools and protocols. Still, the variability in seabed types and changing character that define most seabeds have challenged even the most sophisticated geophysical approaches that take into account compressional and shear wave properties of marine sediments and involve attenuation correlations and grain-to-grain shearing. (e.g., Buckingham 2000, 2005; Williams et al., 2002; Richardson, 1997).

Ambiguities and inconsistencies in datasets collected have remained problematic to offshore engineering operations. In recent times a move to multiple echo energy and signal-shaped sonar systems—operated in tandem with broadened bandwidths, shorter pulse lengths, customized pulse shapes and beam-widths—have provided datasets that capture more complete acoustic responses of sub-bottom properties. These datasets have proven to be more useful in classification-based surficial geology distribution maps, although performances are still subject to a range of degradation effects and calibration is not always easy and often remains ambiguous.

There remains a technology gap for dealing with marine seabed site investigations. Geophysical approaches do not hold the fine scales, density, or multiplicity of data to capture the distribution of inhomogeneous sediment properties with exactitude. This is especially true when the presence of boulders, gas in sediments, lenses and/or pockets of soft or hard sediments characterize a seabed. In addition, the limited sampling scales of geotechnical probes and corers hold little spatial distribution knowledge.

Research and development on a stationary probe that could produce high-energy, deep-penetrating acoustic signals within a volume illustrates a step towards providing meaningful geotechnical data from offshore environments. The concept behind the instrument and methodology, referred to as an “Acoustic Sub-seabed Interrogator” (ASI) by Guigné (1986), is a radical departure from that of conventional geophysical profilers².

The ASI involves 3-dimensional determination of geophysical parameters of the near subsurface with much greater accuracy than is currently attainable using conventional seismic site survey procedures. Increased accuracy of acoustic parameters allows more refined correlations between acoustic and geotechnical properties of sub-seabed soils to be made. The strength of the ASI approach centers on its dynamic use of temporal and spatial resolution, coherence of emitted signals, and dense receiver spacing and location calibration as monitored over a stationary spatial network with horizontal dimensions of greater than 5 meters and typically 12 meters or greater. Through such a stationary acoustic platform, mathematical coherence between echoes is maintained. Dunsiger et

² To address these shortcomings, Guigné experimentally developed a new concept for producing an “acoustic core” answer product, which formed the basis of his PhD research. He presented and defended his PhD thesis to the University of Bath in 1986. It was through the University of Bath that this new geophysical/geotechnical concept was first introduced.

al. (1979) emphasized the importance of coherence in high-resolution mapping. Small misalignments (in the order of 10–20 ms, assuming a velocity in the sediment of 1600 meters per second) between echoes destroy the fabric of the signal response. The ASI's coherent signals and density provide the necessary precision and data to statistically evaluate (in three dimensions) the homogeneity of sedimentary properties and their distribution.

Figure 2 exhibits the technology gap that a wide area acoustic core based on Guigné's ASI concept fills by delivering data from stationary and densely collected acoustic signals.

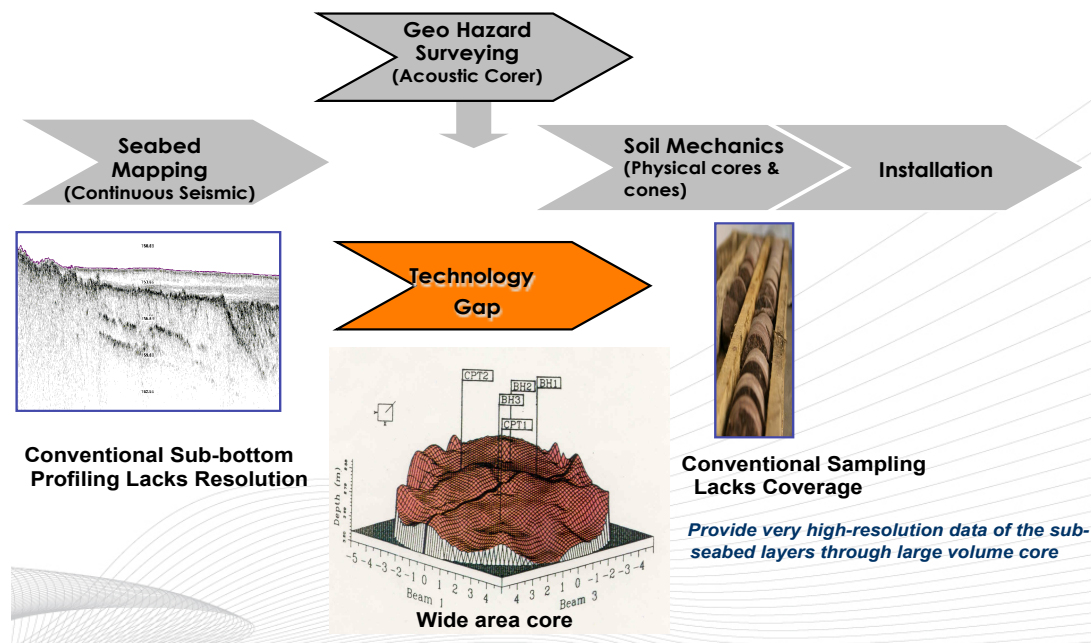


Figure 2: Wide-area acoustic answer product in the form of an “acoustic core” as a means to address the gap in scale for geophysical/geotechnical site investigations. Source: diagram modeled after Guigné’s PhD ASI concept 1986, released in PanGeo Subsea Inc. public marketing material, 2012.

Basically, the receiver and transmitter arrays of an ASI move in a controlled manner in the same plane as the source transmitters for a wide range of possible emergent ray angles. Acoustic reception is made through a phased array of hydrophones, which capture the time histories of the returns and quantify beam spreading for particular reflectors. Focusing on an emergent beam angle of interest is a powerful criterion of an ASI, allowing particularly weak or distorted signals to be analyzed. The dynamic operation of the transmitters and receivers is controlled by a logic that uses real-time processing. The interrogation proceeds in being able to first render the data into a volume whereby a layer-by-layer data analysis can be made to examine both the specular nature of stratigraphic layers and the non-specular responses of discontinuous features such as boulders, with an acoustic core product emerging. A sequential analysis of the time histories is presented graphically. Bathymetry, layer thickness, seismic velocities, attenuation, and other data such as quantifying the extent of seabed inhomogeneity or internal scattering are emphasized to allow for a thorough analysis of what truly characterizes the geotechnical nature of a seabed.

A further product is the presentation of the data in terms of horizontal circular slices through the diameter of the resulting acoustic core (Guigné, 1986). Any of the measured properties of a given horizon can be thus studied and measured. The internal seabed structure of a glaciated region where complex till features are present can thus be deconvoluted and revealed.

This ASI concept introduced the notion of a volumetric 3-dimensional acoustic core answer product, which held spatial lateral scales in meters and tens of meters in depth, thus producing a large areal footprint unprecedented in physical coring with dense specular and non-specular volumetric data collections and visualization imagery as acquired with tens of centimeter definition intervals. The strength of the ASI is founded on having a stationary platform that allows for multiple data acquisitions protocols to be executed in a co-located manner, which morphs into coherent summation (i.e. focusing) of the backscattered wave-field through beam-forming and focusing into the data, hence the term “interrogation.” The focusing methodology relies on adaptive, velocity-corrected, layer-by-layer straight-ray geometrical approximation to capture and accentuate discrete heterogeneous diffuse scattering.

1.4 The Value Proposition For Acoustic Coring

High-resolution sub-seabed acoustic surveys deliver significant value by identifying optimum installation locations when the seabed is not overly complex. However, as seen in the more northern ocean waters where past glaciation influences remain, uncertainties arise in interpreting the acoustic data acquired off of these northern seabeds as these geophysical datasets manifest themselves as inconsistent and variable in intensity. Typically, profiles of the seabed sediments and of their internal boundaries are characterized by spurious reflectors emerging discontinuously and with limited depth of signal penetration into the seabed.

Such responses present uncertainties and hence a lack of confidence in the site investigation database, which in turn becomes a serious problem for those who have to commit to engineering assumptions about the seabed. Deciphering the scattering signal forms returning off boulders and/or till deposits is a major problem as these have peculiar and irregular lateral distributions and placements that mask the coherency in the reflecting acoustic energy. Undetected boulders in the sub-seabed present huge risks for the placement of piles, often leading to enormous time losses and cost overruns associated with either remedial work needed to dislodge a refused pile or its safe abandonment (see Figures 3 and 4).



Figure 3: Typical buried boulders off the East Coast of Canada of similar diameters to the standard piles used offshore. Source: PanGeo Subsea Inc. marketing archive 2010.



Figure 4: Typical diameter of the standard piles used offshore approaching five-meter diameters. Source: PanGeo Subsea Inc. marketing archive 2010

Complementary physical sampling such as boreholes are made problematic by buried boulders and often become of limited value while having been collected at great costs. The questions often posed relate to what exactly constitutes the “real” state of sub-seabed conditions. What is to be believed as being representative for a patch of seabed?

In addition, there is often complete disconnects in what is recorded in the physical sample with what is measured by the in situ geotechnical strength tests conducted, such as for the use and reliance on CPTs. Both of these sampling techniques do not often agree with the geophysical sub-bottom profiles because of their mismatch in spatial and temporal scales used in their discordant resolutions inherent in the targeted information captured.

In discussion with Jon Machin, (Director, Geomarine Ltd.) and paraphrasing from his notes, there is a desire to examine the feasibility of optimizing site investigations for wind farms using geostatistical methods (e.g. Delfimer & Delhomme, 1975; de Smith et al., 2006; Ditlevsen & Madsen, 2007). Stuyts et al. (2011) in particular undertook a study, driven by the perceived industry need to remove the requirement for one geotechnical borehole per wind turbine location. Similarly, the European Union Wind Energy Association, as posted in *The Facts* (European Union, 2010), has stated that the cost of geotechnical survey and foundation construction is currently “great” at an estimated 21% of the total capital cost of an offshore wind-farm.

In the same context, E.ON, a major offshore wind farm developer, has estimated (private communication with Jon Machin and E.ON, 2013) that a total of 1000 boreholes will need to be drilled in 2013 and 2014 if the requirement for having one borehole per wind turbine location is maintained. They state that they find this unacceptable and that new technology is needed. The cost of a geotechnical borehole in the North Sea is approximately \$0.5M (USD) each, suggesting that at least \$250M (USD) will be spent annually on geotechnical boreholes for wind farm projects in the North Sea. Market data suggests that this will represent a doubling or tripling of the current levels of spending, indicating an equipment supply shortage in addition to huge cost implications.

In Stuyts et al.’s paper (2011), the authors developed a Net Present Value (NPV) model, which valued a site depending on the cost of foundation traded against the cost of a site investigation. They were essentially trying to find an optimum value for the site as a

function of the most efficient survey for adequately reliable foundation design purposes. They concluded at the time that current geostatistical techniques were insufficiently powerful to remove the commercial advantage of one borehole per turbine location. The possibility of using geostatistical methods for characterizing the spatial variability of axial pile capacity across a wind farm site was found to be uncertain in results. Stuyts et al.'s geostatistical simulations and analysis noted that spatial variability across wind farm sites are quite large with limited correlation existing between neighboring boreholes for typical spacing of about 1km at their sites studied. They further stated that the heterogeneity of the glacial deposits results in a rapid increase in variance with distance from a borehole. Of significance they suggest that the reliability index required by the engineering codes of practice for 35m long piles cannot be obtained for any of the wind turbines when a borehole is not drilled at each location. Longer piles would be required to achieve the targeted reliability index, resulting in heavily overdesigned foundations.

They concluded in their paper that the risk of failure at uninvestigated locations is too high to lead to cost savings by reducing the size of the site investigation. The net present cost is minimum when a borehole is drilled at each turbine location. One can consider that although their study was competently formulated, it appears that the reason they failed with the geostatistical technique to get the required reliability was because they were correlating between widely spaced borehole stratigraphy (a minimum kilometer apart) with the boreholes having no spatial representation without high quality geophysical data to strengthen their model.

Creating an acoustic core through acoustically interrogating the sub-seabed in a stationary manner holds value in bridging the confidence valley between these borehole and in situ test datasets and addresses the high prohibitive costs faced by the offshore wind industry. This is a compelling argument for pursuing borehole reductions by replacing these with the ASI acoustic core imagery. The ASI approach for acoustic coring holds promise in being able to extend the value of physical cores and CPTs, thereby reducing their number required to obtain confidence in the seabed properties of a site.

Intelligent site investigations that hold confidence in their answers mitigate subsea installation risks for offshore wind turbine foundations, for subsea templates in the relocation of jack-ups rigs, and for the construction of excavated drilling centers. An ASI has been shown to replace and/or reduce the number of physical boreholes in some offshore scenarios (e.g., DONG Energy, SIRI platform site, Danish North Sea, 2011, 2012). Fundamentally, an acoustic core answer product supplements surface seismic and physical cores to achieve more accurate sub-seabed characterization. Used as an "intelligent planning" tool in marine geotechnical site investigations, it can be highly effective in optimizing physical core drilling activities and in mitigating large foundation-based implementation risks and can therefore be used to lower the major site investigation costs that occur during the development phase of offshore wind energy projects.

Figure 5 presents an integrated seabed site investigation proposition for mitigating risks at offshore turbine installation sites. Figure 6 synthesizes and highlights the impact of acoustic interrogations, or "acoustic coring," in comparison with seismic profiling and physical sampling.

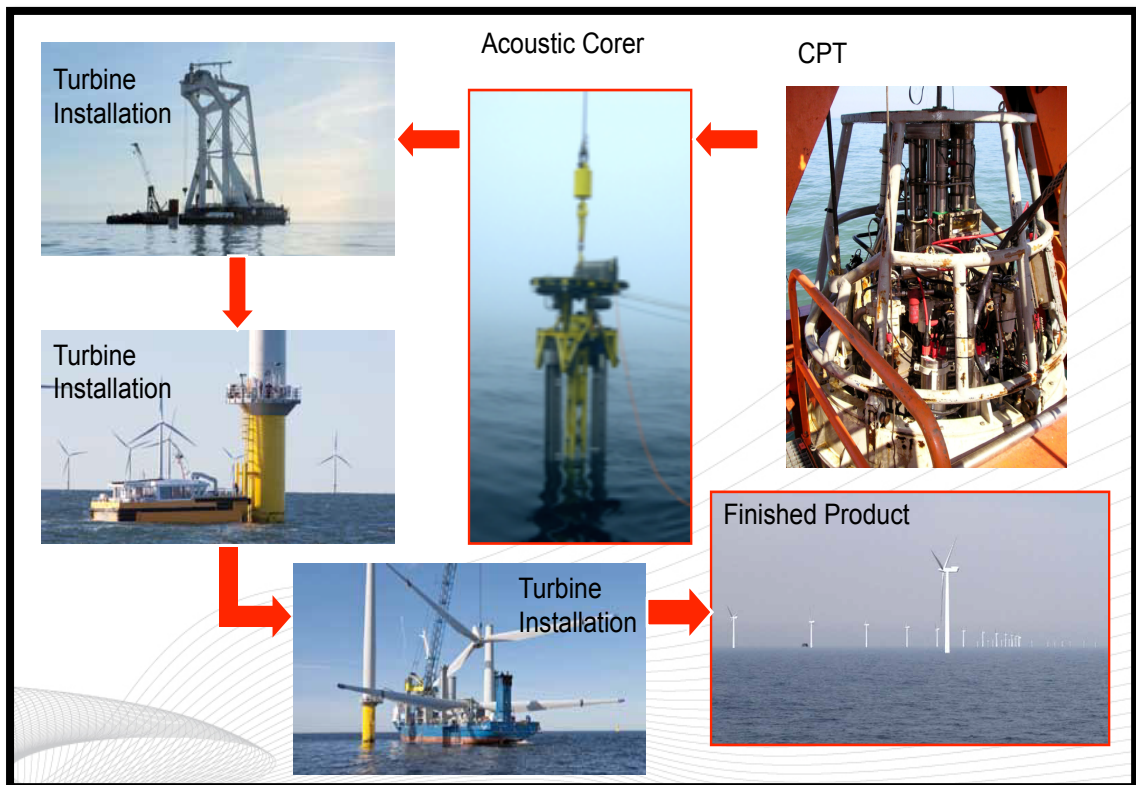


Figure 5: Acoustic interrogations/coring with traditional geotechnical sampling and in situ testing to mitigate wind-farm seabed geotechnical related installation risks. Source: PanGeo Subsea Inc. public marketing material, 2012.)

Examples of early adoption of the use of acoustic interrogations as part of their marine geotechnical investigation, EnBW decided to commission the collection of acoustic cores in the Baltic Sea; eighteen acoustic cores were acquired in water depths of 20m–40m to aid in their planning of wind turbine foundations. EnBW executives responded with the following words in 2010:

In order to mitigate the geological risk for the piling works and therefore to minimize the cost for removal of obstacles offshore we are of the firm opinion that a thorough investigation of the locations is inevitable.... EnBW is making very promising experience with PanGeo's Acoustic Corer system[,] which has successfully been deployed at 6 locations at the Baltic 1 project as well as on 6 locations of the OWF Krieger Flak. We therefore deem it sound proposal to use [PanGeo] for investigating all locations at the OWF Kriegers Flak where piles shall be placed with aim to identify best possible locations for each foundation structure.

Similarly, in 2011, acoustic coring was found to be very strategic at the Anholt Wind-farm location in the Baltic Sea, with 25 acoustic cores collected in a water depth of 15m. This project aimed to help resolve discrepancies in their geotechnical datasets related to their wind turbine foundation installation. Dong Energy executives (2011) commented on the project as follows:

Thank you very much for the good and interesting AC results obtained and reported at Anholt.... The results show that the risk during installation is less than expected before start of the AC activities.... Dong Energy thinks the AC operations have been very successful and have added much value to the project.

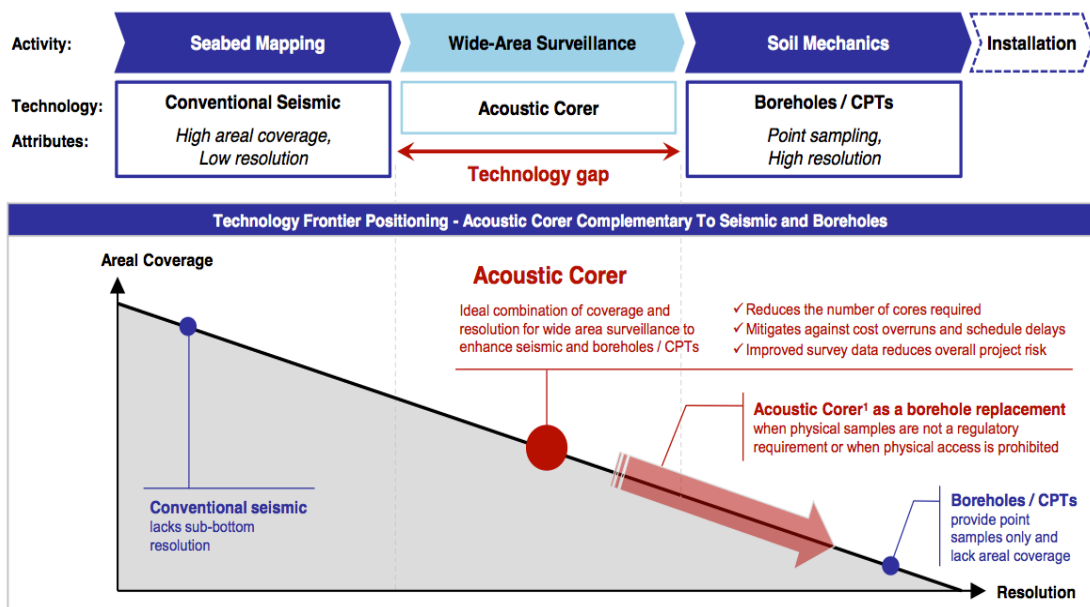


Figure 6: Acoustic interrogations/coring are complementary to seismic and traditional geotechnical sampling and in situ testing where an acoustic core is used in conjunction with CPT to replace a physical core. Source: Simmons & Company International — Information Memorandum on PanGeo Subsea Inc. March 2012.)

In parallel, as difficulties in managing dwindling fish stocks became of international public concern, environmental studies placed importance on acoustic mapping of benthic habitats to unravel the cause and effects of man's influence and offshore activities on such delicate boundary conditions (e.g. Simmonds et al., 2005).

Knowing and quantifying the effects of man's interactions relating to the seabed can develop a better fishery management scheme. Basic knowledge of the water column and seabed conditions is not sensitive enough. The fine scale inherent in habitats cannot be mapped by physical sampling, and acoustic imaging has been most challenging; its imagery requirements are difficult to meet with current sub-bottom profiling practices and thus the appropriate scale on resolutions that can discriminate between textural and structural roughness is lacking. Figures 7 and 8 pictorially highlight the issues of imaging at fine scale discontinuities in benthic habitats.

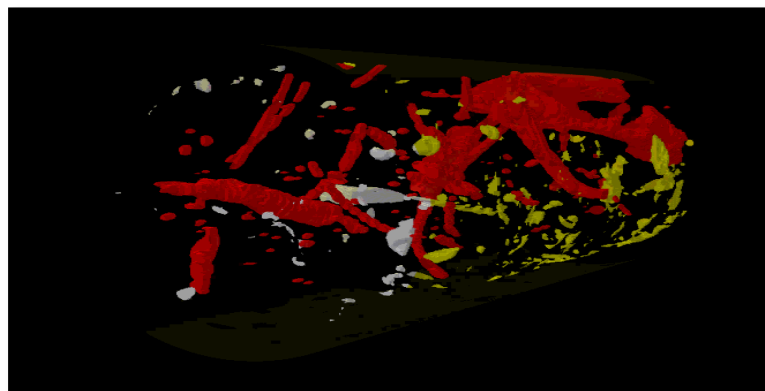


Figure 7: X-Ray CT scan data of a horizontal core (10x10x22cm³) showing shell pieces (yellow) and animal burrows and water pockets (red), which caused high frequency volume scattering; recovered off the coast of Venera Azzura, Italy. Source: Dr. Nicholas Pace SACLANTCEN Report SR-342 and explained in Guigné and Pace, 2007.

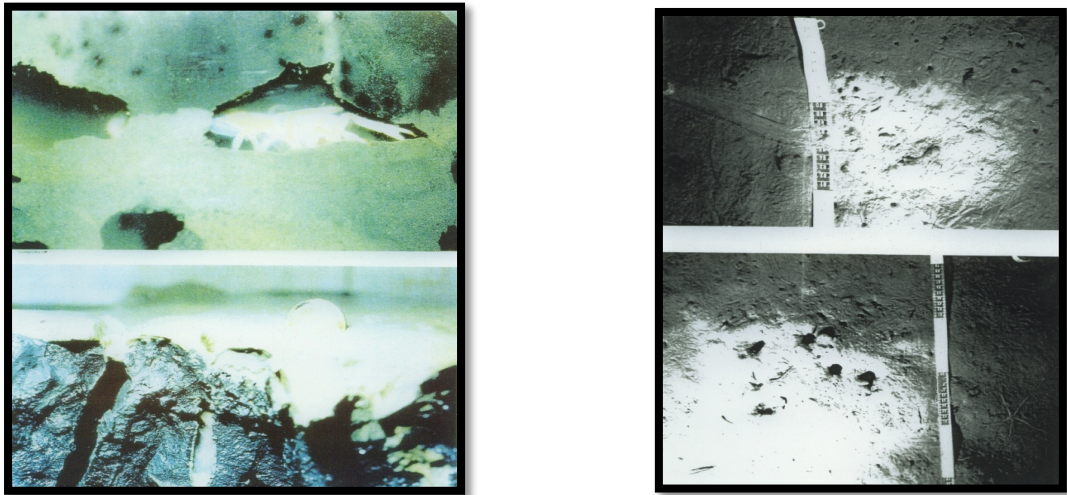


Figure 8: Sample from 0.25m² box corer; the shrimp burrow is approx. 5cm; from the Gulf of St. Lawrence, Canada. Source: Guigné and Pace, 2007.

1.5 The Thesis

This Doctor of Science thesis is a compendium of papers, presentations, and patents that span over 25 years of physics research and engineering implementation studies related to the introduction, market application, and branching outward of new innovative designs based on Guigné's original PhD concept for acoustic sub-seabed interrogations.

The thesis is structured so that each chapter deals with a specific aspect of the ASI's development and application. As noted, Chapter 1 introduced the application context for the idea of an acoustic interrogation of the seabed. The original patent on the Acoustic Sub-Surface Interrogator, which was filed immediately following the Guigné PhD thesis in 1986, is presented in Volume 2, Patents and Publications. The Clark and Guigné 1988 paper and other relevant publications on the ASI that immediately followed set the scene for explaining the challenges in marine geotechnical site investigations and the arguments or value proposition for the ASI concept. These papers are also included in their entirety in Volume 2 as an integral part of this DSc thesis. Guigné and Chin, in 1989, further explained the method and demonstrated a scaled answer product for an inhomogeneous sediment matrix setting the scene for future offshore tests.

Five awarded strategic utility patents on the methodology and embodiment for applications related to the near surface imaging of sediments are included in the thesis (Volume 2). Through this series of patent descriptions, the acoustic building blocks considered fundamental for tackling an acoustic core answer product are exposed and they provide for more detailed explanations on the approach for volumetric mapping of inhomogeneous sediments. This is supplemented with the inclusion of the scientific papers published by the author as also exhibited in Volume 2. These papers express the importance of capturing the way acoustic sediments especially in the form of attenuation redistribute energy. It also brings forth the need for custom designed high frequency, broadband, narrow beam seismic sources and introduces the idea of intensity mapping leading to an areal sound intensity receiver.

Chapter 2 presents the first high-resolution testing of the ASI ideas on an actual seabed, starting with very near-surface imaging. Experimental studies are presented and illustrated with associated published papers that relate to stationary high-definition geophysical capturing of data.

The Guigné et al. study (1991) focused primarily on delineating contaminated lakebeds. The methodology evolved to deliver a unique very near surface acoustic answer product for mapping the health of benthic habitats. This was considered to be pioneering as it was founded on collecting sufficient statistical data, at very high bandwidths, through a spatial array to reveal chaos features of a habitat. The work led to the quantification of the effects of otter trawling on the benthic habitats found on the Grand Banks off of Newfoundland and Labrador, Canada. A key patent emerged, which presented the original designs that evolved for a unique sonar matrix embodiment.

The most elaborate chapter is Chapter 3, as it reveals in detail the evolution of the original multi-beam, multi-aspect view concept designed in Bath in 1986. The chapter attempts to provide an introduction of the early embodiment and of the first acoustic core produced through its various stages of morphology and trials, leading into the present day “Acoustic Corer” engineered solution. The geophysical processing flow used to develop the answer product is described in detail.

The Acoustic Corer technology is rapidly becoming an offshore standard for site-specific de-risking of engineering installations projects offshore Europe. It has gained the attention of the Norwegian Petroleum Directorate for regulatory consideration as a borehole replacement when geotechnical coring cannot be conducted adjacent to existing offshore installations and rigs (ConocoPhillips’s Ekofisk investigation using the Acoustic Corer 2011 and 2012 campaigns). Chapter 4 selects and exposes such case studies and examples of acoustic responses from discontinuous sub-seabed features that characterize complex seabed types and geohazards such as boulders and gas pockets. Where possible the chapter attempts to illustrate and to expose the subtle but detailed rendered character of varying seabed conditions and types.

Increasing the scale to look deeply into the sub-seabed, actually thousands of meters into the Earth, is the potentially evolutionary seismic concept of an acoustic lens called Acoustic Zoom. Similar to the ASI, the Acoustic Zoom methodology relies on stationary layer-by-layer interrogation geophysical techniques. Chapter 5 introduces the physics for Acoustic Zoom imaging and differentiating arguments from conventional seismic migration practices. A description of the first full scale pilot and preliminary results are revealed. What is exciting is the acquisition of high frequencies at depth with an emphasis on securing, through beam-forming and steering into the data, non-specular imagery. This is a work in progress focused on continuing and expanding on the original 1986 ASI ideas. Three comprehensive patents were awarded for this ASI Acoustic Zoom evolution (these are included in Volume 2).

Finally, Chapter Five, the last chapter, brings forth a vision for the next generation of ASI whereby the goal is to formulate through the stitching of discrete cells a very large diameter ASI with an acoustic core diameter product measured volumetrically in units greater than 50 meters lengths, widths, and depths. This is discussed in detail in this chapter by presenting the descriptions written in 2012 for a comprehensive patent that was filed in 2012 and is awaiting examination (to be published in September 2013 by the USA Patent Office). The chapter also concludes with a revisiting of what has changed in marine geotechnical engineering since the Clark and Guigné 1988 paper suggested and predicts the trends for future seabed site investigations.

Hence this Doctor of Science thesis is a collation of published papers, patents and added descriptions on the development, application, and future directions for the concept and application of “acoustic interrogating” of the seabed. In many ways it expands on 26 years of research work completing the author’s 1986 PhD thesis with the “chapters that earlier got away”!

References Cited

- Avery, C.S. (2011). *Seafloor massive sulphides: assessment of sustainable mining potential through an iterative decision-making framework*. Master's thesis Engineering, Queen's University, Kingston, Ontario.
- Buckingham, M. J. (2000). Wave propagation, stress relaxation, and grain-to-grain shearing in saturated, unconsolidated marine sediments, *J. Acoust. Soc. Am.*, 108 (6), 2796-2815.
- Buckingham, M. J. (2005). Compressional and shear wave properties of marine sediments: Comparisons between theory and data, *J. Acoust. Soc. Am.*, 117 (1), 137-152.
- Buckingham, M. J., & Richardson, M.D. (2002). On tone burst measurements of sound speed and attenuation in sandy marine sediments, *IEEE J. Ocean. Eng.*, 27 (3), 429-453.
- Chilès, J.P. & Delfiner, P. (1999). *Geostatistics: Modeling Spatial Uncertainty*, Wiley series in probability and statistics (pp. 695). Hoboken, New Jersey: Wiley.
- Clark J. I., & Guigné, J. Y. (1988). Twenty-fifth anniversary special paper: Marine geotechnical engineering in Canada. *Canadian Geotechnical Journal*, 25, 179-198.
- de Smith, M., Goodchild, M., and Longley, P. (2006). *Geospatial analysis, a comprehensive guide*. 3rd edition. Leicester: Matador.
- Delfiner, P. & Delhomme, J.P. (1975). Optimum interpolation by kriging. In: *Display and Analysis of Spatial Data*, 96–114. (ed. by J.C. Davis & M.J. McCullagh). London: Wiley
- De Ruiter, J., Fugro-Cescob V., and Fox, D.A. (1975). Site Investigation for North Sea forties field. *Proceedings, Seventh Annual, Offshore Technology Conference, Houston*, (Vol. 11) pp. 21-37.
- Ditlevsen, O. & Madsen, H.O. (2007). Structural Reliability Methods. Technical University of Denmark. June- September 2007.
- Dowse, B. A. (1986) *Canadian in situ development needs—offshore and onshore. Workshop on Geotechnical In situ Testing for Canadian Offshore*. Bedford Institute of Oceanography, Dartmouth, N.S.
- Dunsiger, A. D., Cochranen A., and Vetter W, J. (1979). Seabed characterization from broadband acoustic echosounding with scattering models. *IEEE Journal of Oceanic Engineering*, OE-4 (3): 94- 106.
- Greenlaw, C.F., Holliday D.V., McGehee D.E. (2004). High-frequency scattering from saturated sand sediments; *J. Acoust. Soc. Am.*, 115 (6), pp. 2818-2823
- Guigné, J. Y. (1986). *The concept, design and experimental evaluation of "acoustic sub-seabed interrogation."* Ph.D. thesis, University of Bath, Bath, UK.
- Guigné, J.Y, and Pace N.G, (2007). *An analytical acoustic framework to quantify the health of benthic habitats*. 2nd International Conference And Exhibition, Underwater Acoustic Measurements: Technologies And Results, F.O.R.T.H., Crete.

Hart, P.E., Pohlman J.W., Lorenson T.D., Edwards B.D., (2011). *Beaufort sea deep-water gas hydrate recovery from a seafloor mound in a region of widespread BSR occurrence*; Proceedings of the 7th International Conference on Gas Hydrates (ICGH 2011), Edinburgh, Scotland, United Kingdom, July 17-21.

Hovem, J. M. (2007). *Marine Acoustics. The Physics of Sound in Underwater Environments*. Applied Research Laboratories, The University of Texas at Austin, Texas, US. (Peninsula Publishing, Los Altos, CA, USA)

Jardine, R., Chow, F., Overy, R., and Standing, J. (2005). *ICP Design Methods for Driven Piles in Sands and Clays*, Thomas Telford, pp. 105.

Kinsler L. E., Fray A. R., Coppens A.B., J.V. Sanders J. V. (2000). *Fundamentals of Acoustics, 4th edn*. New York, NY: Wiley.

Kullerud L., Beaudoin Y.C., Poussart J.N., Prokosch P., Sund H. (2013). *The Arctic Ocean and UNCLOS Article 76: Are There Any Commons*; Series: NATO Science for Peace and Security Series C: Environmental Security

Lurton, X. (2002). *An Introduction to Underwater Acoustics: Principles and Applications*. Chichester, U.K.: Springer Praxis.

Marsland A. (1985). *The influence of geological processes and test procedures on measured evaluated parameters*. Advances in underwater technology and offshore engineering; 3, Offshore site investigation. Graham and Trotman Ltd., London, England, pp. 231-252.

Mayer L. A. (1979). The origin of fine scale acoustic stratigraphy in deep-sea carbonates. *Journal of Geophysical Research*, 84(B11): 6177-6184.

Mayer L. A., & Leblanc I. R. (1983). *The chirp sonar: A new quantitative high-resolution profiling system*. Proceedings, Institute of Acoustics Conference: Acoustics and the Seabed, University of Bath: Bath, England.

Pace N.G. SACLANTCEN Report SR-342

Papadakis E.P. (2000). *Ultrasonic Instruments and Devices*, (Academic, London)

Richardson, M. D., (1997). *Attenuation of shear waves in near surface sediments*. In: *High-Frequency Acoustics in Shallow Water*. SACLANTCEN Conference Proceedings series CP-45, La Spezia, Italy, N.G. Pace, E. Pouliquen, O. Bergem and A.P. Lyons (Eds), pp. 451-457.

Ruffell, J. P., Romeril, P., M., and Jones, K., W. (1985). *A critique of arctic marine site investigation techniques*. Proceedings, Arctic '85, Civil Engineering in the Arctic Offshore, San Francisco, CA, ASCE, pp. 122-136.

Sempler, M., and Rigden, W. J. (1983). Site investigation for Magnus. *Fifteenth Annual Offshore Technology Conference*, Houston, Vol.I, pp.205-216.

Stuyts, B. Vissers, V, Cathie, D. N. (Cathie Associates), Dorfeldt, S. (Offshore Wind Technology). (2010) "Optimizing Site Investigations and Pile Design for Wind Farms Using Geostatistical Methods: A case study", *Frontiers in Offshore Geotechnics*, Perth Australia, 8-10; ISFOG II.

Telford, W.A., Geldart, L.P., Sheriff, R.E. (1990). *Applied Geophysics*. (2nd ed.) Cambridge.

Turcotte, D. (1990). "Fractals in Geophysics and Geology", *Pure and Applied Geophysics*
Simmonds J. and MacLennan D., 2005. *Fishery Acoustics. Theory and Practice*. (2nd ed.) Oxford, UK: Blackwell.

Waite A.D. (2002). *Sonar for Practicing Engineers*. (3rd ed.) (Wiley, Chichester, UK)

Williams, K. L., Jackson D.R., Thorsos E.I., Tang D. Schock S.G., 2002. Comparison of sound speed and attenuation measured in a sandy sediment to predictions based on the Biot theory of porous media, *IEEE J. Ocean. Eng.*, 27 (3), pp. 413-428.

Wind Energy, The Facts, European Wind Energy Association – 2000; Official Publications of the European Union.

Volume 2 - Associated And Related Patents/Publications By The Author

Guigné, J.Y. (1990). *USA Patent No. 4,924,449*. United States Patent Office.

Clark, J.I. & Guigné, J.Y. (1988). Marine Geotechnical Engineering in Canada. *Canadian Geotechnical Journal*. 25(2), 179-198.

Guigné, J.Y. & Chin, V.H. (1989). Acoustic Imaging of an Inhomogeneous Sediment Matrix. *Marine Geophysical Researches*. 11, 301-317.

DEVELOPING THE ANSWER PRODUCT STARTING AT THE SEABED

2.1 Capturing the Character of the Near Surface Sediments

This chapter delineates the importance of the fine scales and of the characteristics that form the near surface sediments of a seabed. The near surface constitutes the setting of benthic habitats (e.g. Boudreau et al., 2005; Brown and Blondel, 2009; Brown et al., 2011) and its micro-complexity establishes the acoustical requirements for mapping the profoundly delicate balance implied in the fine scale functions of a whole ecosystem.

To be able to image the fine stratigraphy of the very near surface high frequency, broad bandwidth short pulses are required. An overview of seabed-mapping technologies in the context of marine habitat classification is presented in detail by Kenny and colleagues (Kenny et al., 2003). An application of non-linear acoustics, the parametric array, is ideally suited to deliver the appropriate broad bandwidth signals at the fine scale required (see papers by Guigné et al., 1989, 1991, in Volume 2 for explanations on applying a terminated or truncated parametric array). By stacking different secondary frequencies, coherent delineation of the fine seabed stratigraphy can be produced (Guigné et al., 1991).

Figure 9 is an example of using such an approach. The profiles were taken by the author in Hamilton Harbour, Ontario Canada.

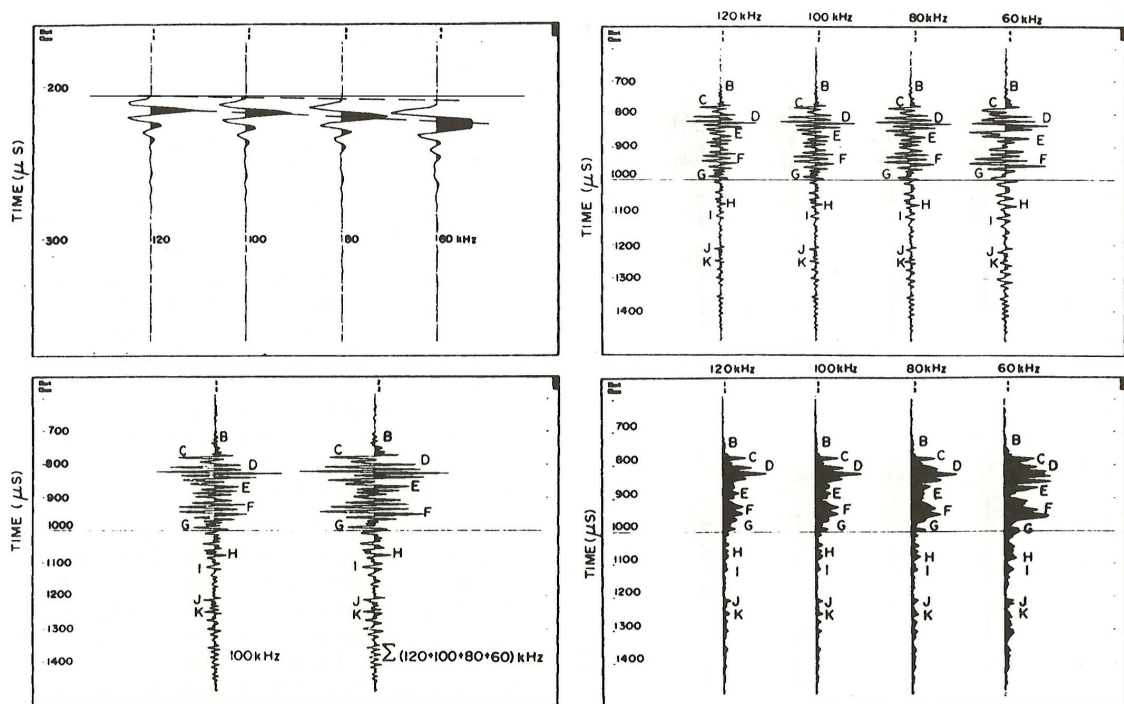


Figure 9: Dispersion test of the water column (top left) with time histories of the acoustic pulse recorded at the test site (top right). Frequency summation (bottom left). Instantaneous amplitudes for the time histories of the acoustic data recorded at test site using four different frequencies (bottom right). Source: Guigné et al., 1991.

2.2 Imaging the Fabric and Texture of the Benthic Habitat

The health of benthic habitats and ecosystems depends upon the exchange of nutrients and thus a maximum surface-to-volume ratio in their physical habitat structures (e.g.

Guigné & Pace, 2007). In the case of benthic fauna, the benthos is the burrow walls, tubes, and galleries of the infauna. Animal structures in the sediment provide an inherent chaos and thus tend to maximize the efficiency of nutrient or micro-particulates energy transfer through their habitat walls (e.g. Schwinghamer, Guigné, & Liu, 1993). Capturing statistically the state and distribution of these internal fine scale sedimentary structures in the natural sediment fabric is a difficult task to achieve and requires close adherence to the resolving properties of acoustic soundings along with attention to the experimental design. These constraining requirements must be dealt with in view of the vast conflicting spatial scales that a seabed habitat poses. Kraan and his colleagues (2010) discussed the role of environmental variables in structuring landscape-scale species distributions in seafloor habitats. The challenge is to spatially acquire information at a high enough resolution (e.g. in millimeter voxels) to map the micro-internal sedimentary dimensions within a vast areal seafloor existence.

To meet this challenge a form of ASI was applied to interrogate the near-surface sediments. The acoustic sampling tool employed was called Benthic-DRUMS, and it was designed to provide a 3-dimensional acoustic snapshot of biogenic activity within surficial sediments to a depth of 15–20 centimetres below the seafloor. The Benthic-DRUMS's design encompassed four rows of ten independent, broadband parametric array based transmitters to deliver pencil beam signals of high frequencies into the seabed. Matching receivers were co-located to the transmitters (refer to Figure 10).



Figure 10: Benthic-DRUMS hardware with electronic bottle seen in red attached to a tripod the transmitter/receiver head is seen in blue (top). The bottom figure presents an enlarged view of the transmitter head showing the four rows; the white tipped probes are the receivers. Source: Personal photographs taken in 1993.

The strength of the interrogating sampling method employed by Benthic-DRUMS is a statistical “leap frog” random multiple spot-sampling approach, which removes ambiguities tied to having an absolute position on the seabed; absolute location of data related to a specific seabed spot does not necessarily transfer into statistical representation of a seabed region’s character (refer to Figure 11).

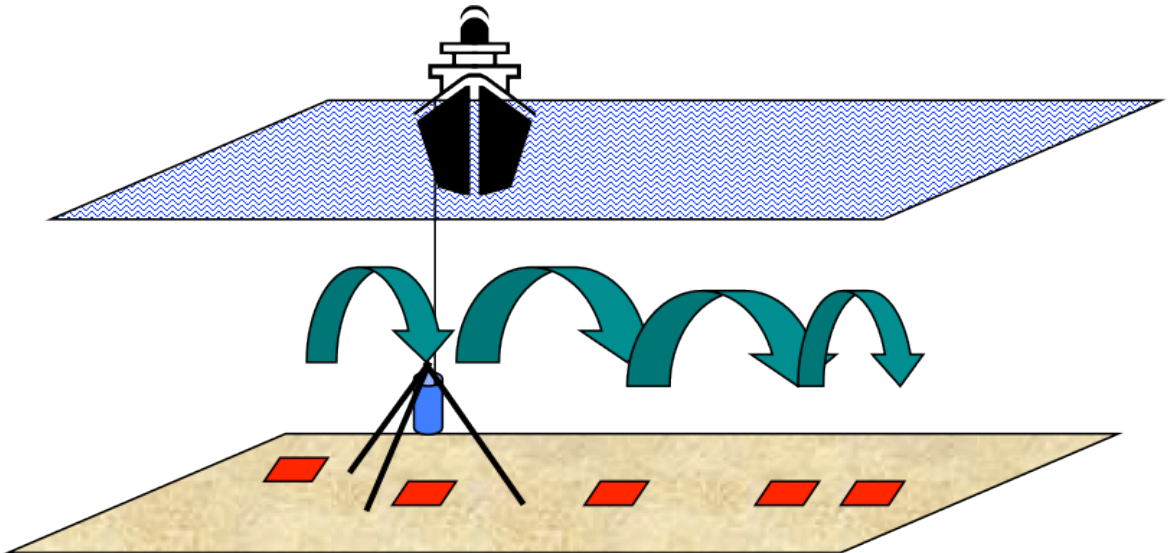


Figure 11: Data acquisition occurs at each location with a sequential transmission/receive script executed in seconds for each of the forty positions with hundreds of locally distributed sounding positions taken over a region of interest, to form a sufficient database for significant statistical treatment to be considered. Source: based on author’s sketches in 2002.

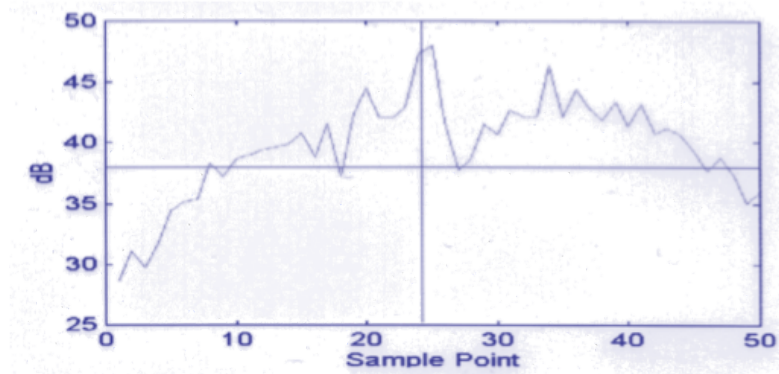
2.3 Capturing the Essence of Roughness

To deliver a 3-dimensional acoustic snapshot of biogenic activity within surficial sediments, statistical processing techniques are applied. The acoustic data are transformed to a measure of structural ‘roughness’ through the use of fractals as a measure of internal complexity from which the health of the seabed is inferred. There are several definitions and points to consider related to fractals. Typically, fractals can be seen as a series of irregular and fragmented patterns (Mandelbrot, 1977; Burrough, 1981; Bradbury et al., 1984; Turcotte, 1990; Breyer & Snow, 1992). There are many computational algorithm developments related to the creation and application of fractal dimensions (e.g. Fournier et al., 1982; Clarke, 1986; Clarke & Schweizer, 1991) and of their scaling as applied to remote sense data (e.g. Goodchild, 1980; Lovejoy et al., 1986; Saupe, 1988; Lam & Quattrochi, 1992; Jaggi et al., 1993).

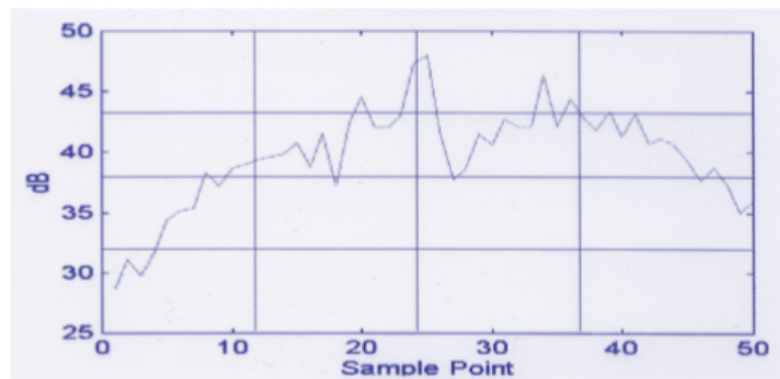
In general, the Hausdorff–Besicovitch dimension found in fractals is strictly greater than the corresponding topological dimension (Mandelbrot, 1977). In view of applying fractal assignments to acoustic signals as in the case of the ASI’s acoustic interrogations of a seabed to quantify a calculus of heterogeneity, the use of fractals becomes a measure of their irregularity and roughness (refer to Fox and Hayes, 1985; Elliot, 1989; Dubuc, 1989; and Milne, 1992, as they suggested various fractal definitions as a measure of “roughness”). Fractal applications to seafloors proved useful and the resulting dimensions helped to characterize heterogeneity (e.g. Malinverno, 1989; and Mareschal, 1989).

There are typically two main sets of fractals: self-similar, where a small part of the fractal can be used to generate the whole of a larger version (Milne,1990), and self-affine, where reductions or enlargements need to be rescaled by different factors in the vertical and horizontal coordinates to resemble the original (Malinverno,1990). Figure 12 illustrates three rescaling steps used to acquire a fractal dimension off of the ASI's acoustic signals. Figure 13 exhibits the resultant fractal curve.

Step 1: Divide into one-half; number of boxes to cover the curve =4



Step 2: Divide into one-quarter; number of boxes to cover the curve =10



Step 3: Divide into one-eighth; number of boxes to cover the curve =24

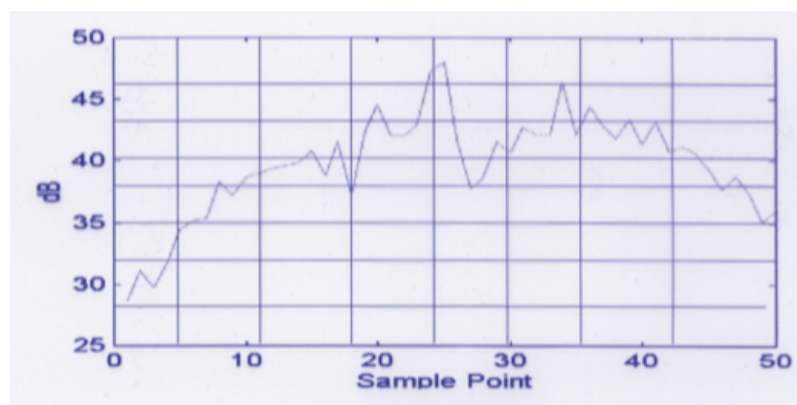


Figure 12: An example of rescaling steps to acquire a fractal dimension from a signal.
Source: Redrawn from works of Malinverno, 1990.

Resultant Fractal Dimension

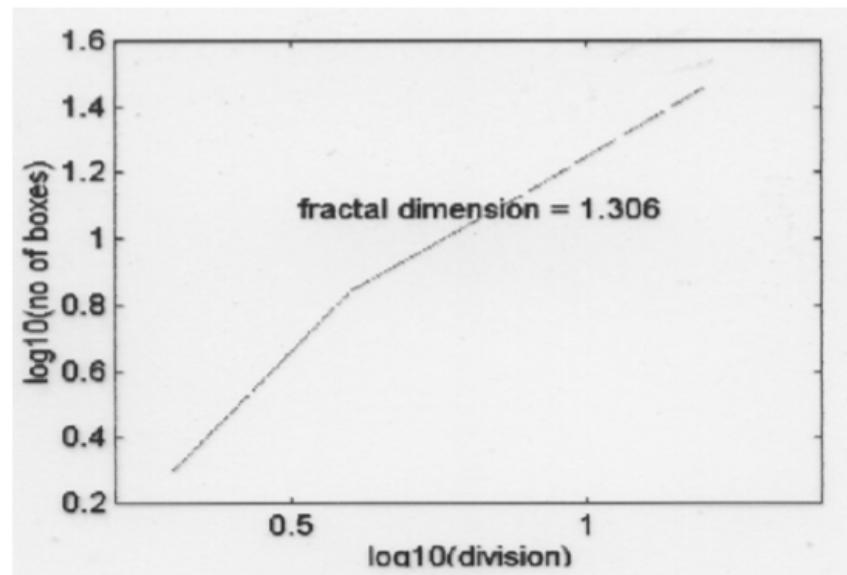


Figure 13: An example of acquiring a fractal dimension from a signal. Source: Redrawn from works of Malinverno, 1990.

2.4 The Benthic Application

The ASI's processing premise is to quantify the “roughness” variances found in a sub-seabed. Given that a natural homogeneous seabed void of biological life would have a low roughness measure, thus revealing a constant sediment character or of a fabric texture, then an active, fauna-filled seabed would be noted for a seabed similar in grain size and distribution composition but presenting a high roughness factor influenced by the internal micro-structures that form a habitat.

This statistical roughness analysis of acoustic interrogations is an ideal attribute to use for monitoring seabed health in zones around a potential environmental hazard source such as industrial outfall sites and marine mining exploitation is taking place, or where man-made seabed interactions are present and potentially dominant such as marine oil and gas installations.

From 1991 to 1993, ASI experimental data off the Grand Banks (East Coast, Canada) were collected using a modified Benthic-DRUMS video-grab sampler (refer to pictorials presented in Figures 14 to 16, which illustrate the hardware arrangement). The acoustic interrogations were established to ensonify the seabed through the opening of the grab sampler jaws, co-located with the video camera, which provided photographs of the seabed patch before closure of the jaws occurred and before a physical sample would be recovered (Figure 15). This ensures an exceptional one-to-one superposition of datasets.

In Figure 17, two examples of typical acoustic signals collected from the Benthic-DRUMS stacked are presented. Their time histories correspond to two regions, one a controlled protected region where the seabed is considered to be under natural influences and a second region where repetitive trawling has occurred. The trawled region exhibits less sharpness in the energy curve of the signals captured from varying depths into the near-surface seabed.

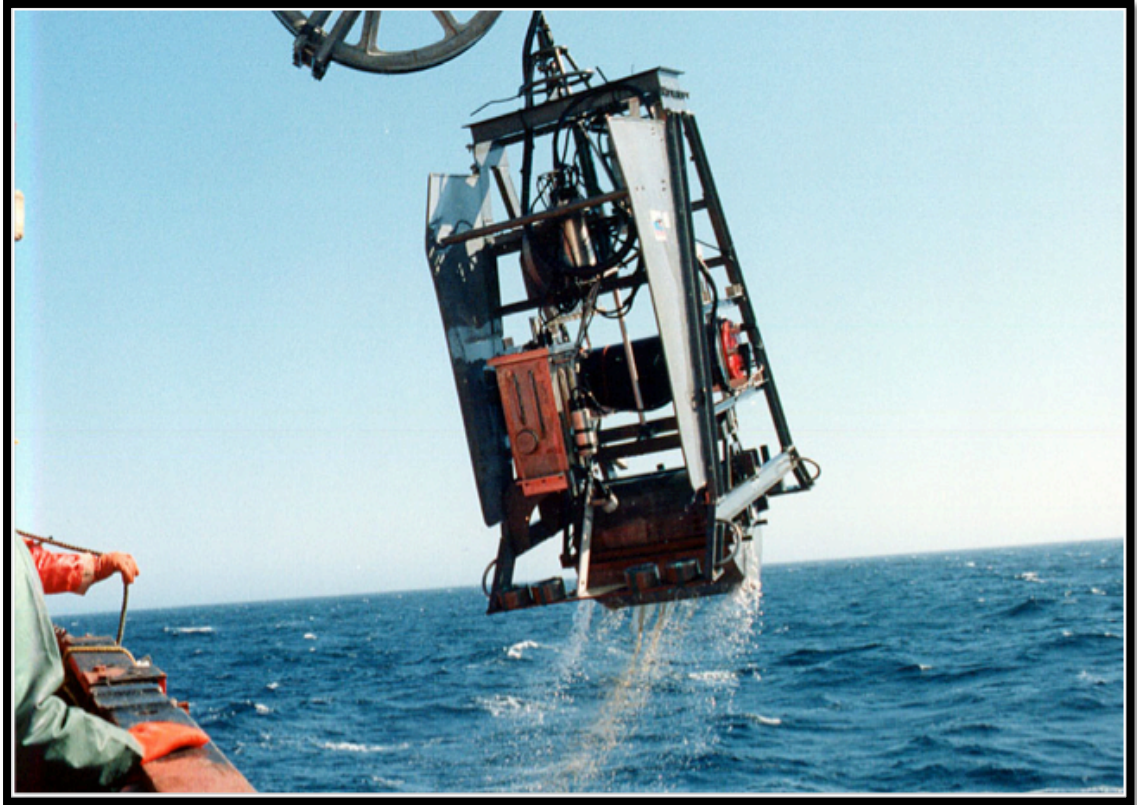


Figure 14: Recovery of Instrument after acoustic interrogations. Source: Author's archived photographs taken from the MV Parizeau in ocean waters over the Grand Banks, offshore Newfoundland and Labrador in 1992

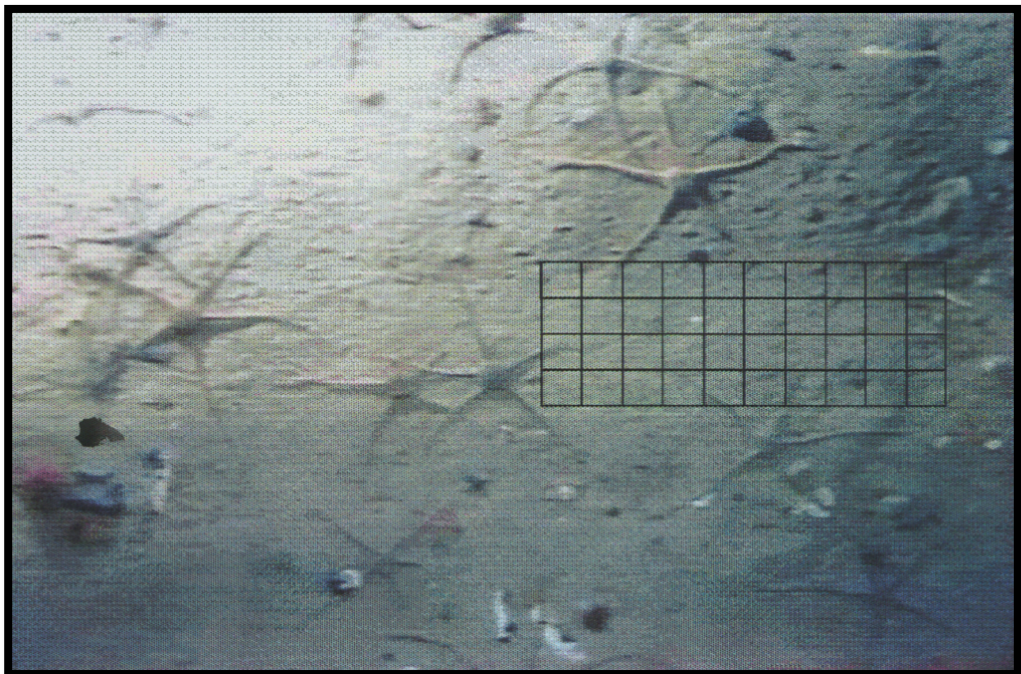


Figure 15: Photographic example taken of seabed as seen through the open jaws of the sampler, with acoustic grid superimposed onto the photograph to exactly show where the forty acoustic soundings occurred. Source: Author's archived photographs taken from the MV Parizeau in ocean waters over the Grand Banks, offshore Newfoundland and Labrador in 1992.

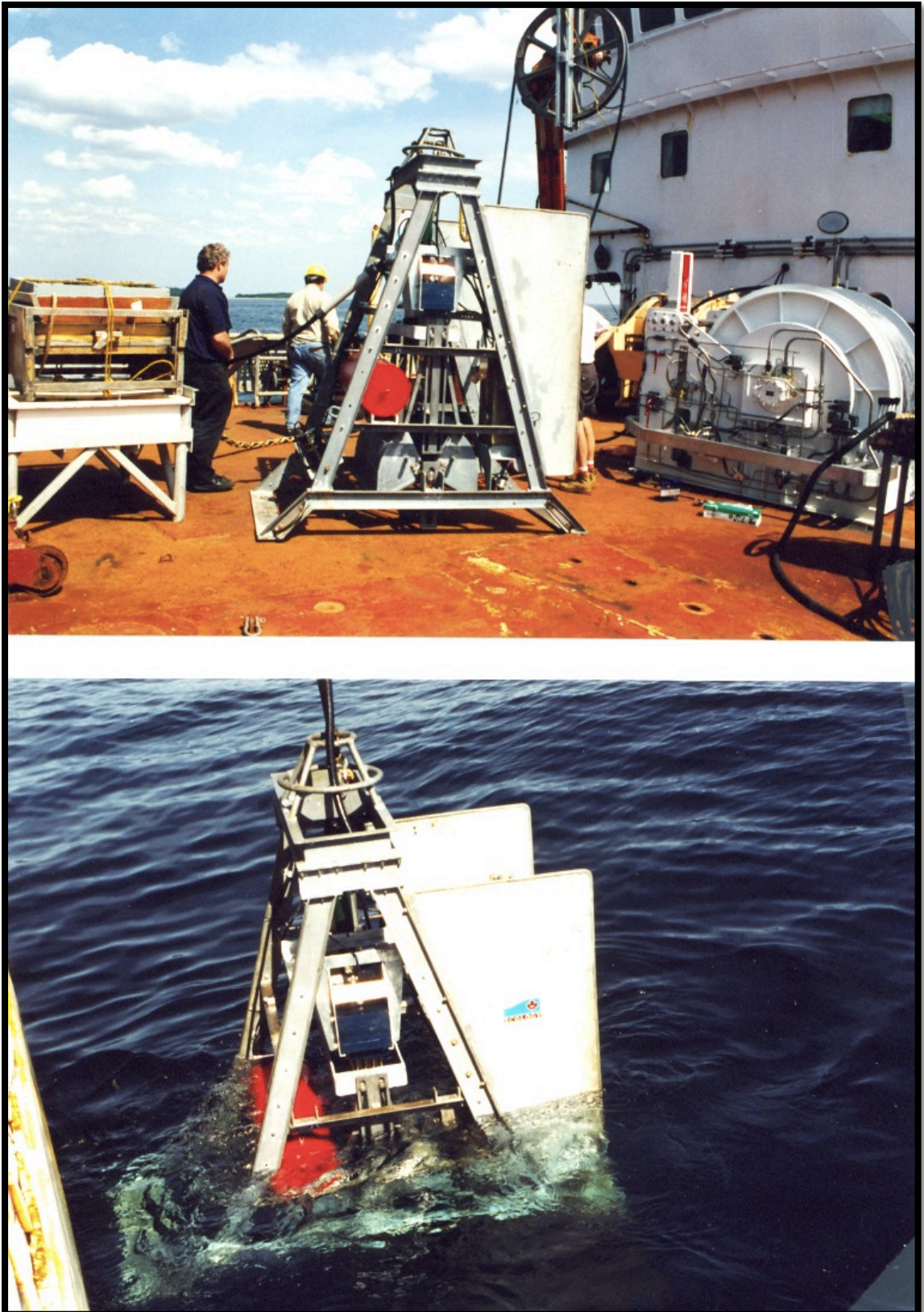


Figure 16: Composite photographs of the hardware; the red electronic bottle is nestled into the framework with the its blue transducer of forty transmitting elements with receivers suspended by the cylindrical video camera, above the open jaws of the grab sampler forming the base of the instrument. Source: Author's archived photographs taken off the vessel - MV Parizeau in ocean waters over the Grand Banks, offshore Newfoundland and Labrador in 1992.

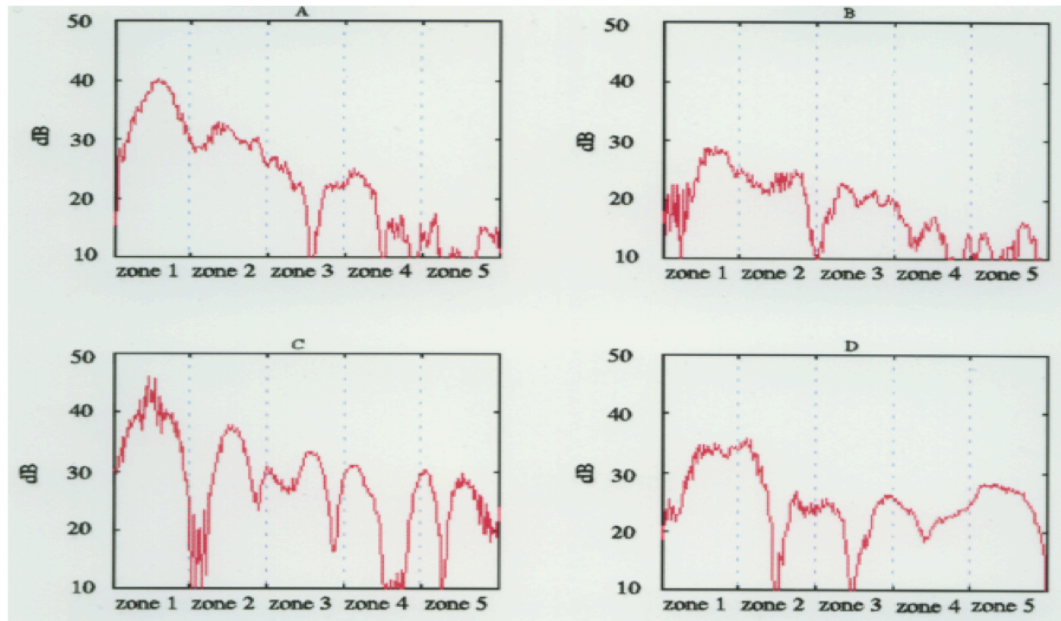


Figure 17: Hilbert -transformed time histories for untrawled (A and C) and trawled (B and D) sites; highlighting comparisons in a descending five depth strata. Source: Schwinghamer et al., 1993.

When fractals are applied to a large dataset collected, comparisons can be observed for the area trawled versus the natural area controlled (refer to Figure 18). The statistics gathered were deemed to be robust, representative of the situation, and highly significant; this is exposed in a comprehensive manner in Schwinghamer et al.'s work (1993) and in Guigné and Pace's study (2007).

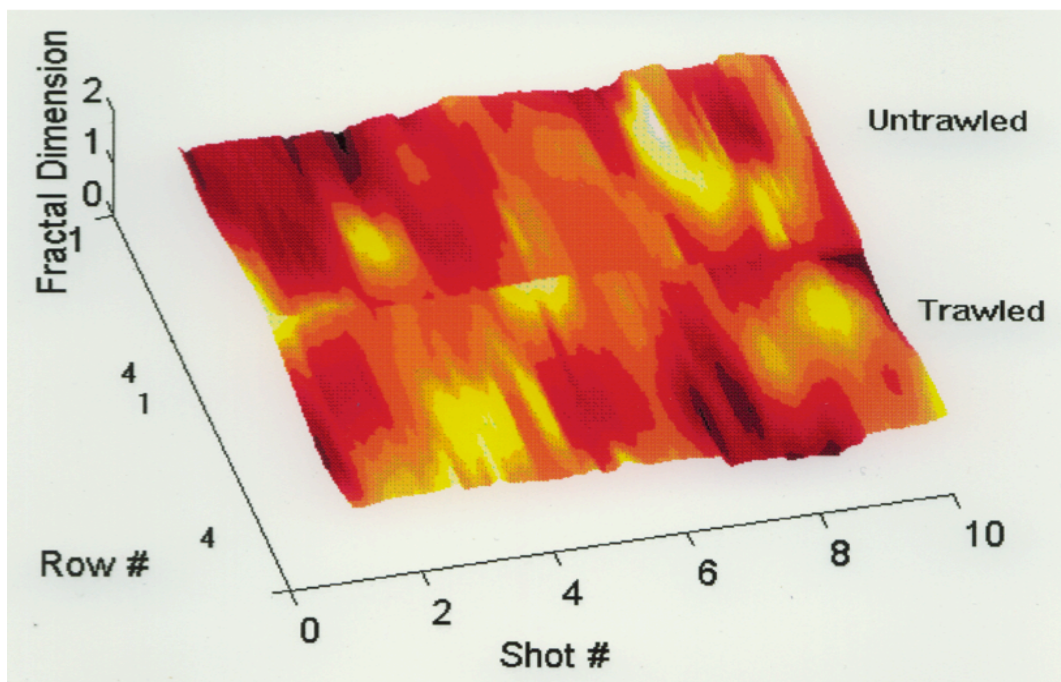


Figure 18: Decreasing fractal values (white to yellow, red, black) plotted across the forty element sonar sliced by descending zones (where each zone represents a thickness of 1.6 cm) comparing the responses for the untrawled to the natural trawled site. Source: Modified from Schwinghamer et al.,1993 and in Guigné and Pace, 2007.

2.5 Significance And Value

The acoustic measurements made by this ASI benthic application indicated a significant, demonstrable effect of trawling, which in preliminary analysis of the surrounding biological and bulk sediment properties did not reveal prominent changes.

In Schwinghamer, Guigné and Liu (1993), the following was reported:

Physical disturbances of ecosystems result in loss of biological organization. While disturbed systems are physically degraded to a simpler abiotic structure with a greater random component, more complex, biogenically organized systems are characterized by higher levels of structural and dynamic unpredictability, or chaos. Our experimental results demonstrated a reduction in this structural chaos, measured by a consistent and significant decrease in the fractal of high resolution acoustic return signals, in a sandy seabed physically disturbed by otter trawling.... In our analysis of chaos, we introduce a quantitative measure of the structural effects of physical disturbance on the benthic habitat.

Ecosystem function depends upon the exchange of materials and thus a maximum surface to volume ratio in the exchange structures, which in the benthos are the burrow walls, tubes, and galleries of the infauna (Rhoads, 1974; Aller, 1988; Pelegri & Blackburn, 1974). A decrease in the fractal of such a system will result in a decrease in its exchange capacity. Animal structures in the sediment, like plant structures in terrestrial ecosystems, are designed to maximize the chaos of the system and thus maximize the efficiency of material and energy transfer. Therefore, the reduction of the fractal by a physical disturbance in an exchange system like the sandy marine seabed attacks the system in its primary functional role. The disturbance caused by experimental otter trawling, if chronic, may have profound impacts on the functioning of the whole ecosystem by reduction of the exchange capacity. Reduction of fine-scale complexity by trawling indicates a much more basic disturbance of the benthic system than would be indicated if immediate mortality of some species were the most notable effect.

This is the value of our ASI's fine-scale acoustic interrogations in the near-seabed of approximately 10 centimeter penetrations with 1 millimeter voxels: delivering unprecedented fractal distributions and revealing the benthic habitat micro-structures and texture.

References Cited

- Aller, R.C. (1988). Benthic fauna and biogeochemical processes in marine sediments: the role of burrow structures. *In* "Nitrogen cycling in coastal marine environments" (Blackburn, T.H. & Sorensen, J., eds). Wiley, Chichester. pp. 301-338.
- Boudreau, B.P., Algar, C., Johnson, B.D., Croudace, I., Reed, A., Furukawa, Y., Dorgan, K.M., Jumars, P.A., Grader, A.S., Gardiner, B.S. (2005). Bubble growth and rise in soft sediments. *Geology, (Fall)* 33, 517-520
- Bradbury, R.J., Reichelt, R.E. & Green, D.G. (1984). Fractals in ecology: methods and interpretation . *Marine Ecology Progress Series* 14, 295-96.
- Breyer, S.P. and Snow, R.S. (1992). Drainage basin perimeters: a fractal significance. *Geomorphology* 5, 143-57.

- Brown, C.J., Blondel, P. (2009). Developments in the application of multibeam sonar backscatter for seafloor habitat mapping. *Applied Acoustics, The Application Of Underwater Acoustics For Seabed Habitat Mapping*. (70)10, 1242-1247.
- Brown, C.J., Smith, S.J., Lawton, P., Anderson, J.T. (2011). Benthic habitat mapping: A review of progress towards improved understanding of the spatial ecology of the seafloor using acoustic techniques. *Estuarine, Coastal And Shelf Science*. (92) 3, 502-520.
- Burrough, P.A. (1981). Fractal dimensions of landscape and other environmental data. *Nature* 294, 240-242.
- Clarke, K.C. (1986). Computation of the fractal dimension of topographic surfaces using the triangular prism surface area method. *Computers and Geosciences* 12, 713-22.
- Clarke, K.C. & Schweizer, D.M. (1991). Measuring the fractal dimension of natural surfaces using a robust fractal estimator. *Cartography and Geographic Information Systems* 18, 37-47.
- Dubuc, B., Quiniou, J.F., Roques-Carmes, C., Tricot, C., Zucker, S.W. (1989). Evaluating the fractal dimension of profiles. *Phys. Rev. A* (39), 1500–1512
- Elliot, J.K. (1989). An investigation of the change in surface roughness through time on the foreland of Austre Okstindbreen, north Norway. *Computers and Geosciences* 15, 209-217.
- Fournier, A., Fussel, D., & Carpenter, L. (1982). Computer rendering of stochastic models. *Communications of the ACM* 25, 371-84.
- Fox, C.G. and Hayes, D.E. (1985). Quantitative methods for analyzing the roughness of the sea floor. *Reviews of Geophysics* 23, 1-48.
- Goodchild, M.F. (1980). Fractals and the accuracy of geographical measures. *Mathematical Geology* 20, 615-620.
- Guigné, J.Y. & Pace, N.G. (2007). An Analytical Acoustic Framework to Quantify the Health of Benthic Habitats, in proceedings: *Underwater Acoustic Measurements - Technologies & Results; Special session on "Habitat mapping and underwater acoustics."* 2nd International Conference & Exhibition, Crete.
- Jaggi, S., Quattrochi, D.A. & Lam, N.S. (1993). Implementation and operation of three fractal measurement algorithms for analysis of remote-sensing data. *Computers and Geosciences* 19, 745-67.
- Kenny, A.J., Cato, I. M., Desprez, M., Fader, G., Schuttenhelm, R.T.E., Side, J. (2003). An overview of seabed-mapping technologies in the context of marine habitat classification. *ICES J. Marine Science* (60)2, 411-418
- Kraan, C., Aarts, G., van der Meer, J., Piersma, T. (2010). The role of environmental variables in structuring landscape-scale species distributions in seafloor habitats. *Ecology* 91:1583–1590.
- Lam, N.S. and Quattrochi, A.A. (1992). On the issue of scale, resolution, and fractal analysis in the mapping sciences. *The Professional Geographer* 44, 88-98.

Lovejoy, S. & Schertzer, D. (1986). Scale invariance, symmetries, fractals, and stochastic simulations of atmospheric phenomena. *Bulletin of the American Meteorological Society* 67, 209-232.

Malinverno, A. (1990). A simple method to estimate the fractal dimension of a self-affine series. *Geophysical Research Letters*, (17)11, 1953-1956.

Malinverno, A. (1989). Testing linear models of sea-floor topography. *Pure and Applied Geophysics* 131, 139-55.

Mandelbrot, B.B. (1982). *The fractal geometry of nature*. San Francisco, California: W. H. Freeman.

Mareschal, J. (1989). Fractal reconstruction of sea-floor topography. *Pure and Applied Geophysics* 131, 165-177.

Milne, B. (1992). Spatial Aggregation and Neutral Models in Fractal Landscapes. *The American Naturalist* (139)1, 32-57.

Saupe, D. 1988: *Algorithms for random fractals* (Peitgen, H.O. and Saupe, D., eds) *In* The sciences of fractal images, New York: Springer-Verlag.

Pelegri, S.P., & Blackburn, T.H. (1974). Bioturbation effects of the amphipod *Corophium volutator* on microbial nitrogen transformations in marine sediments. *Mar.Biol.* (Berlin), 121: 253-258.

Rhoads, D.C. (1974). Organism-sediment relationships on the muddy seafloor. *Oceanogr.Mar.Biol.Annu.Rev.* 12, 263-300.

Schwinghamer, P., Gordon, Jr., D.C., Rowell, T.W., Prena, J., McKeown, D.L., Sonnichsen, G., & Guigné, J.Y. (1998). Effects of Experimental Otter Trawling on Surficial Sediment Properties of a Sandy-Bottom Ecosystem on the Grand Banks of Newfoundland. *Conservation Biology*(12)6, 1215-1222.

Volume 2 – Associated And Related Patents/Publications By The Author

Guigné, J.Y., Chin, V.H. and Solomon, S.M., (1989). Acoustic Attenuation Measurements Using Parametric Arrays. *Ultrasonics* 27 (Sept), 229-301.

Guigné, J.Y., Pace, N.G. & Chin, V.H. (1989). Dynamic Extraction of Sediment Attenuation From Sub-Bottom Acoustic Data. *Journal of Geophysical Research* 94 (B5) May.

Klein, K. & Guigné, J.Y. (1995). Near-field Acoustic Intensity Mapping Using a Closed Surface. *Journal of Acoustical Society of America*. 98(2), Pt. 1.

Guigné, J.Y. (1990). *USA Patent No. 4,955,001*. USA Patent Office.

Guigné, J.Y., Rukavina, N., Hunt, P., & Ford, J.S. (1991). An Acoustic Parametric Array for Measuring the Thickness and Stratigraphy of Contaminated Sediments. *Journal of Great Lakes Research*. 17(1),120-131.

Schwinghamer, P., J.Y. Guigné, & Siu, W.C. (1996). Quantifying the Impact of Trawling on Benthic Habitat Using High Resolution Acoustics and Chaos Theory. *Canadian Journal of Fisheries and Aquatic Sciences*.

Guigné, J.Y. & Pace, N.G. (2007). An Analytical Acoustic Framework to Quantify the Health of Benthic Habitats, in proceedings: *Underwater Acoustic Measurements - Technologies & Results; Special session on "Habitat mapping and underwater acoustics."* 2nd International Conference & Exhibition, Crete.

Schwinghamer, P., Gordon, Jr., D.C., Rowell, T.W., Prena, J., McKeown, D.L., Sonnichsen, G. & Guigné, J.Y. (1998). Effects of Experimental Otter Trawling on Surficial Sediment Properties of a Sandy-Bottom Ecosystem on the Grand Banks of Newfoundland. *Conservation Biology*. 12(6), 1215-1222.

Guigné, J.Y. (2002). *US Patent No. 6,738,311*. USA Patent Office.

IMAGING INTO THE SUB-SEABED

3.1 Creating a Prototype Design

The first ASI design was experimented with in 1990, 1991, 1992, and 1993. English et al. (1991) described the design, which involved a platform that supported sixteen planar sparker transmitters in an octagonal polyethylene framework held by an aluminum outer structure³ (refer to Buogo and Cannelli [2002] for an insight into sparker based transmitters and profilers). A twelve-meter-long rotating boom at the apex of the instrument provided support to twelve equally spaced calibrated hydrophones. Figure 19 shows the assembly and presents the positions of the sparker transmitters and receivers.

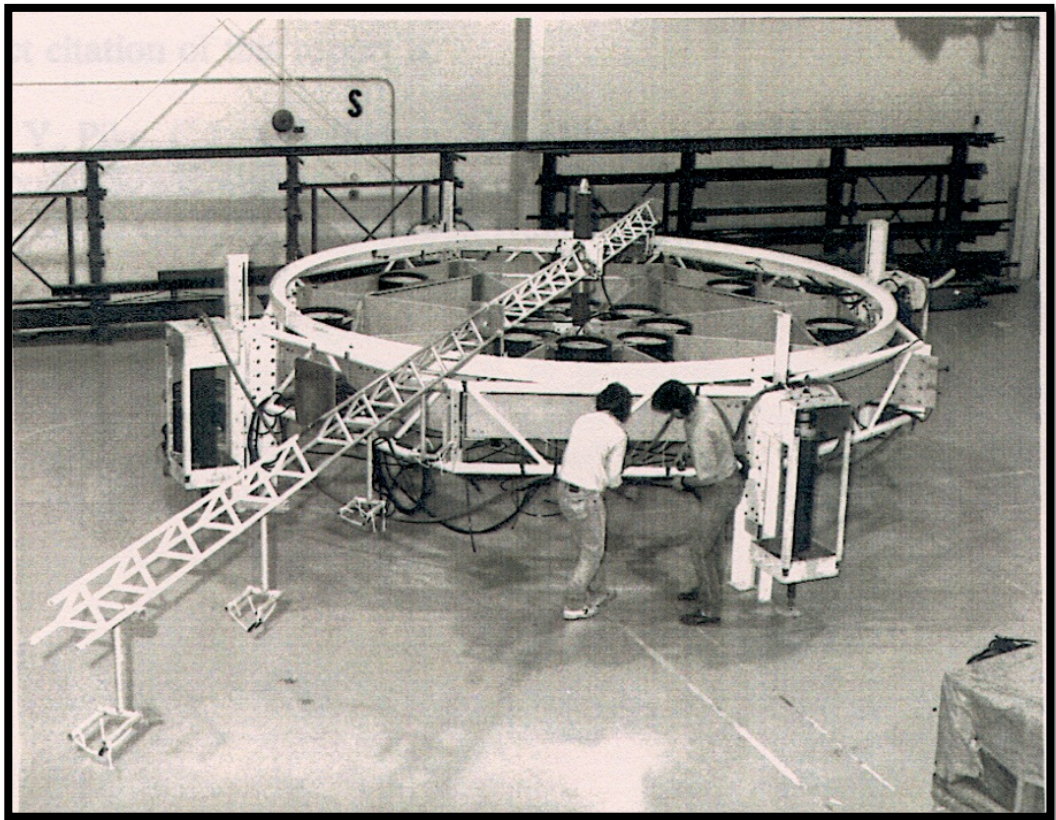


Figure 19: First embodiment of the ASI using sixteen sparker sources as transmitters
Source: Author's archived photographs, circa 1990 from personal photo library.

The 12 receivers along the boom were rotated during data collection and aligned with four transmitters to form a transmitter receiving row called a "beam." This data acquisition protocol delivered four linear "beams" of data. The resulting data would then be processed and subsequently translated into a 3D volumetric imagery having a minimum ten-meter diameter with a depth of penetration in the sub-seabed of over ten meters.

³ The implementation involved the participation of a number of geophysicists: S. Inkpen, C. Pike, J. English and Peter Hunt under the leadership of J.Y. Guigné and sponsorship of Mobil Oil Canada Limited, Gulf Canada Resources Limited, Petro-Canada Resources Limited, and Esso Resources Canada Limited. Advances in wavelet analysis on the acoustic data was led by C. Pike as part of his PhD research, supervised by Guigné and released in his thesis in 1998.

3.2 Proof of Concept Trials

The first deployment and experimentation of the ASI took place in various harbours in Newfoundland and Labrador (see Figure 20).

A major experiment then took place in the near shore zone off Terrenceville, Newfoundland and Labrador, in 1991 (Guigné et al., 1991; Inkpen et al., 1991; Pike, 1998). Figure 21 illustrates the configuration used in the data acquisition.



Figure 20: Deployment of ASI in 1991 off of a pier in Newfoundland and Labrador. Source: Author's archived photographs, circa 1991.

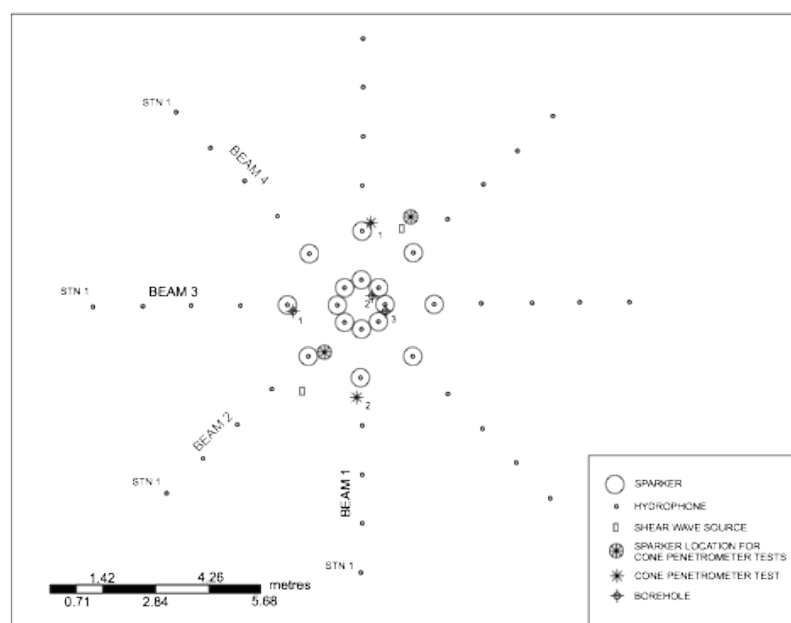


Figure 21: Data acquisition geometry. Source: From Guigné et al., 1991

3.3 Formulating a First Answer Product

The processing of the data had two data flows based on high frequency sparker soundings and low frequency sparker soundings. These signals would follow separate processing routines starting from trace edits, statics, bandpass filters, common depth point sorts, normal moveout, stacks and interpolations before being merged into a final resulting data beam. This is expressed in Figure 22 (refer to Guigné et al. [1991] and Inkpen et al. [1991]).

The intent was to create many folds that are the number of source/receiver combinations that sample the same common depth point. This was coupled with 50 trace stacks at two power levels. Hence, basically two complete surveys were carried out at two power levels, 480 Joules and 1080 Joules, and then fused together forming four distinct panels of 2D seismic. Figures 23, 24, 25, and 26 exhibit the four brute stack data panels or 2D rendered seismic “beams,” or slices, of processed data as acquired at the Terrenceville site (see Mueller, C. [2005]; Scheidhauer et al. [2005] for details on seismic processing):

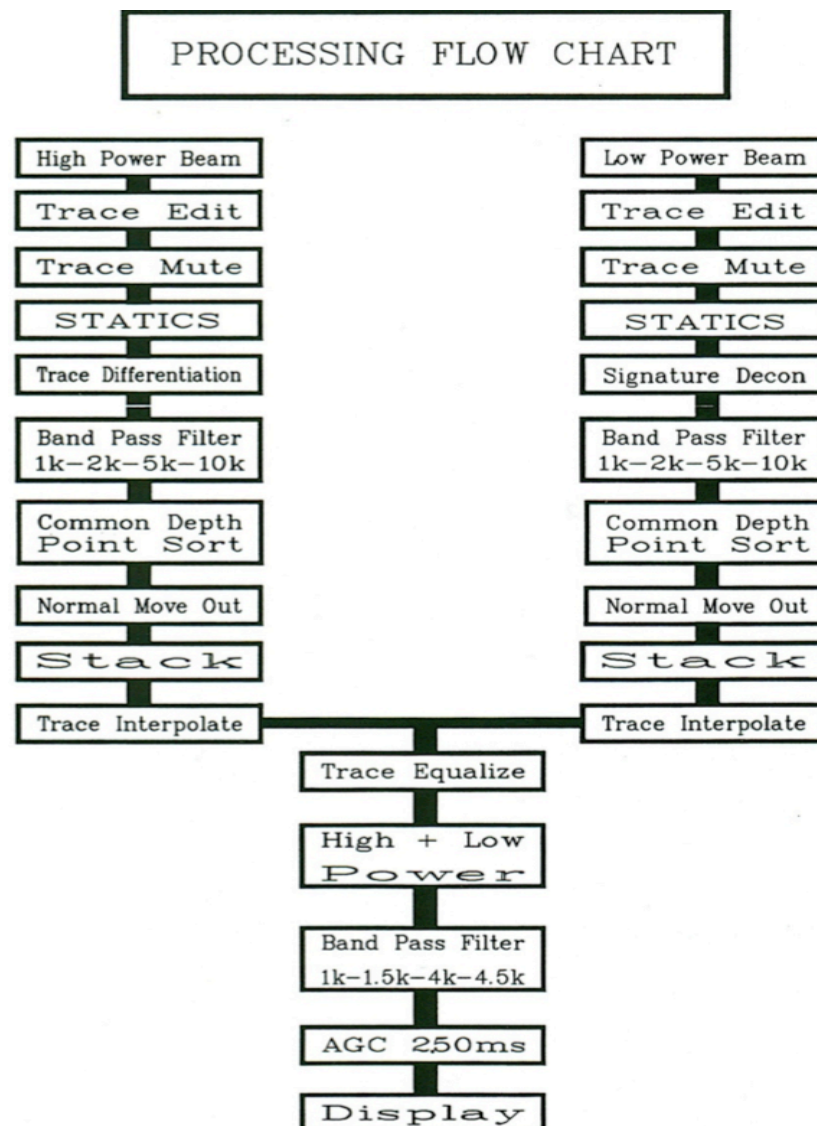


Figure 22: Processing sequence. Source: From Guigné et al., 1991 and Inkpen et al., 1991.

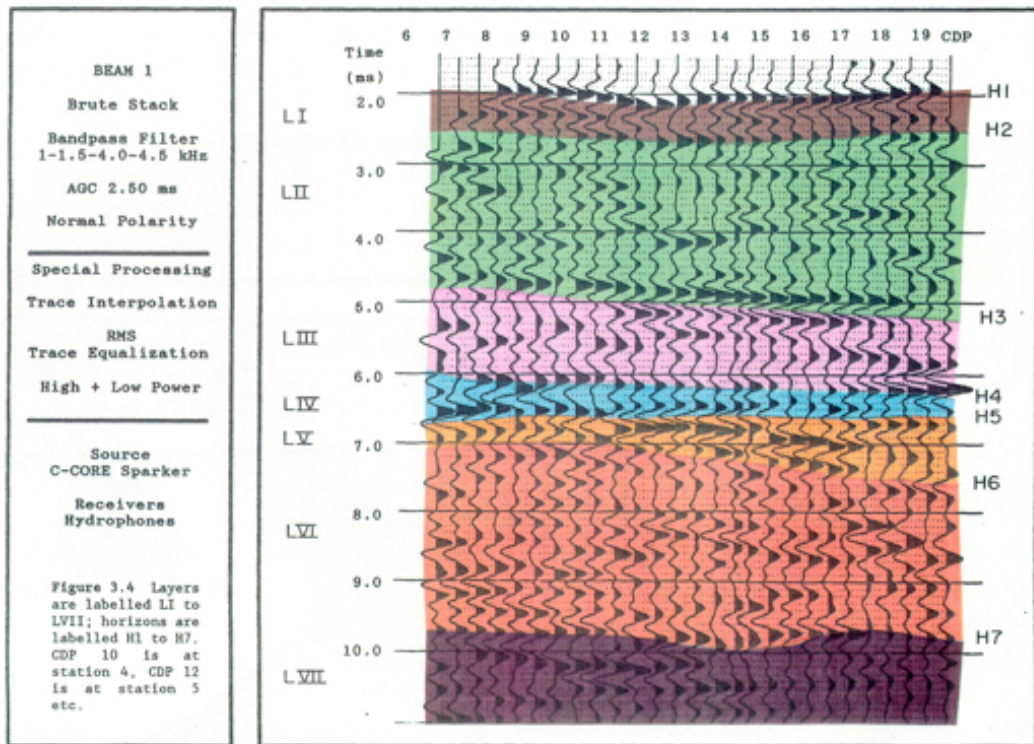


Figure 23: Beam 1 data panel. Source: From Guigné et al., 1991 and from Pike, 1998's thesis.

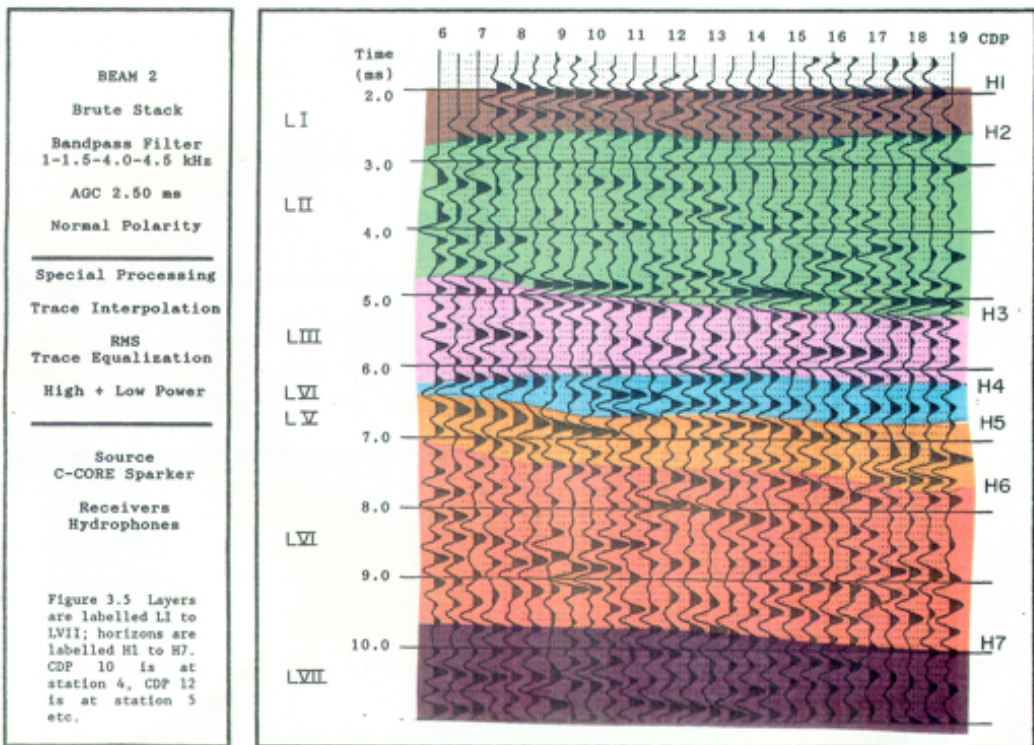


Figure 24: Beam 2 data panel. Source: From Guigné et al., 1991 and from Pike, 1998's thesis.

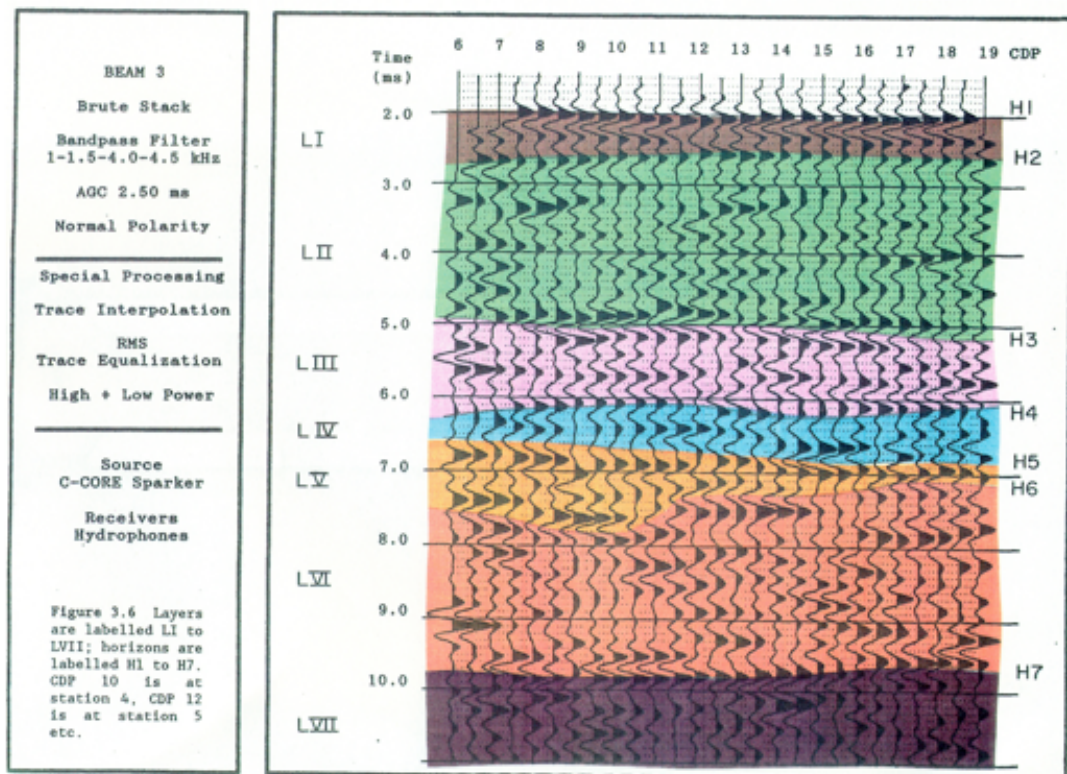


Figure 25: Beam 3 data panel. Source: From Guigné et al.,1991 and from Pike, 1998's thesis.

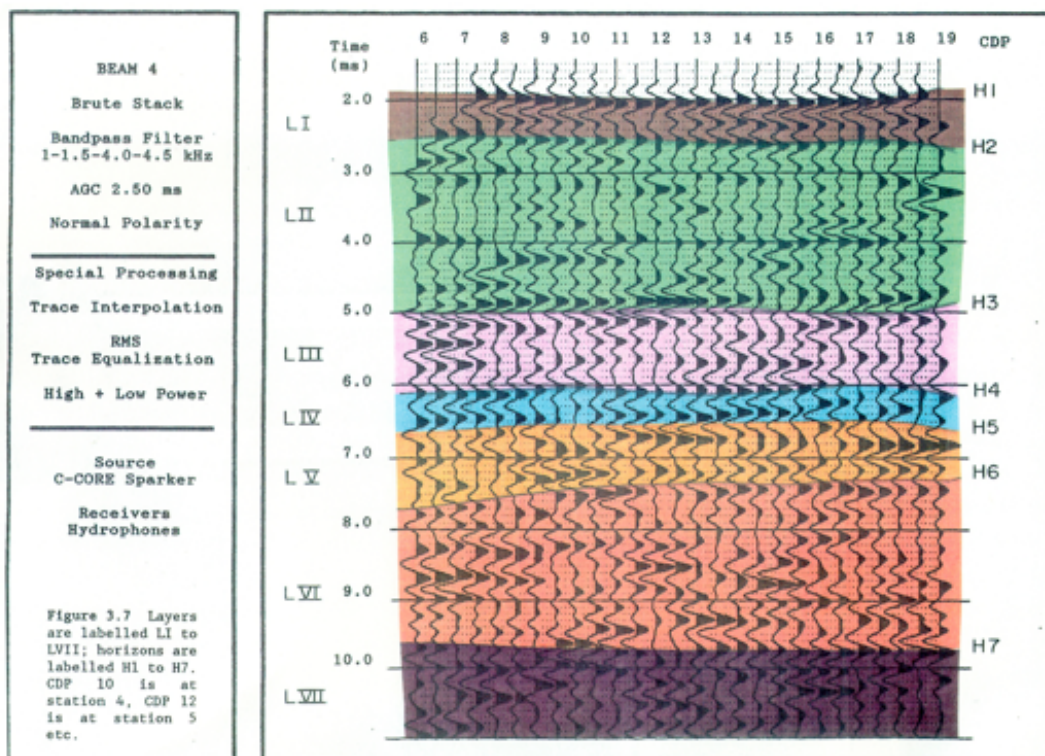


Figure 26: Beam 4 data panel. Source: From Guigné et al.,1991 and from Pike, 1998's thesis.

The ASI data gathering and processing was transformed into a set of stratigraphic contour and isopachyte layer plots for the Terrenceville site (see Figures 27, 28, and 29).

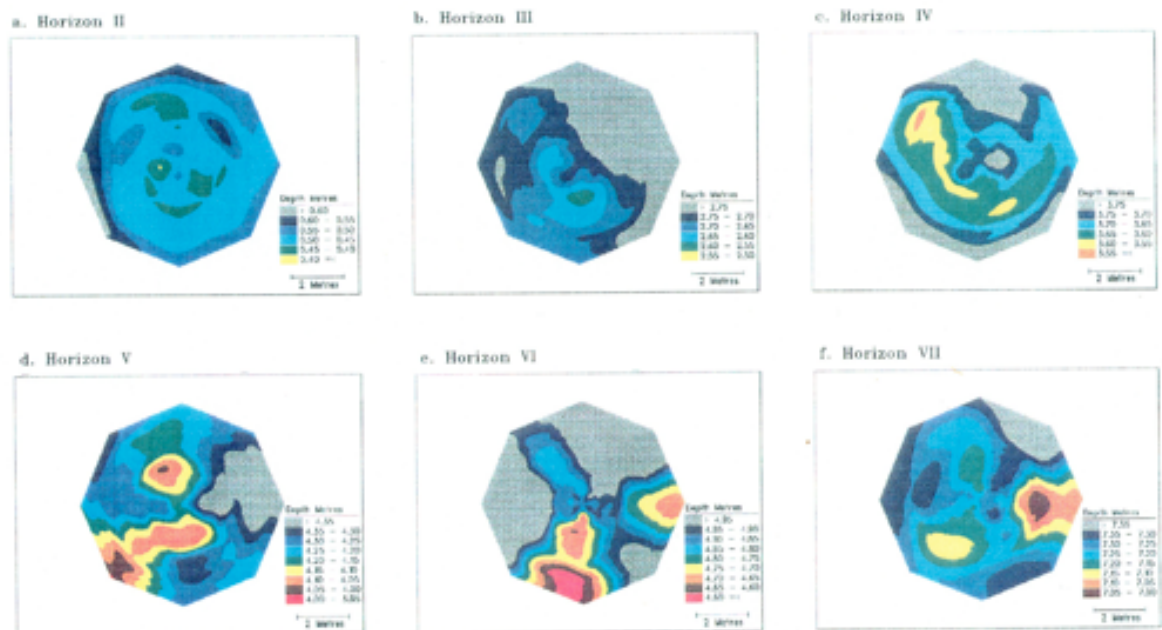


Figure 27: Depth Contours From Depth Cross-sections. Source: From Guigné et al., 1991 and from Pike, C. 1998's thesis.

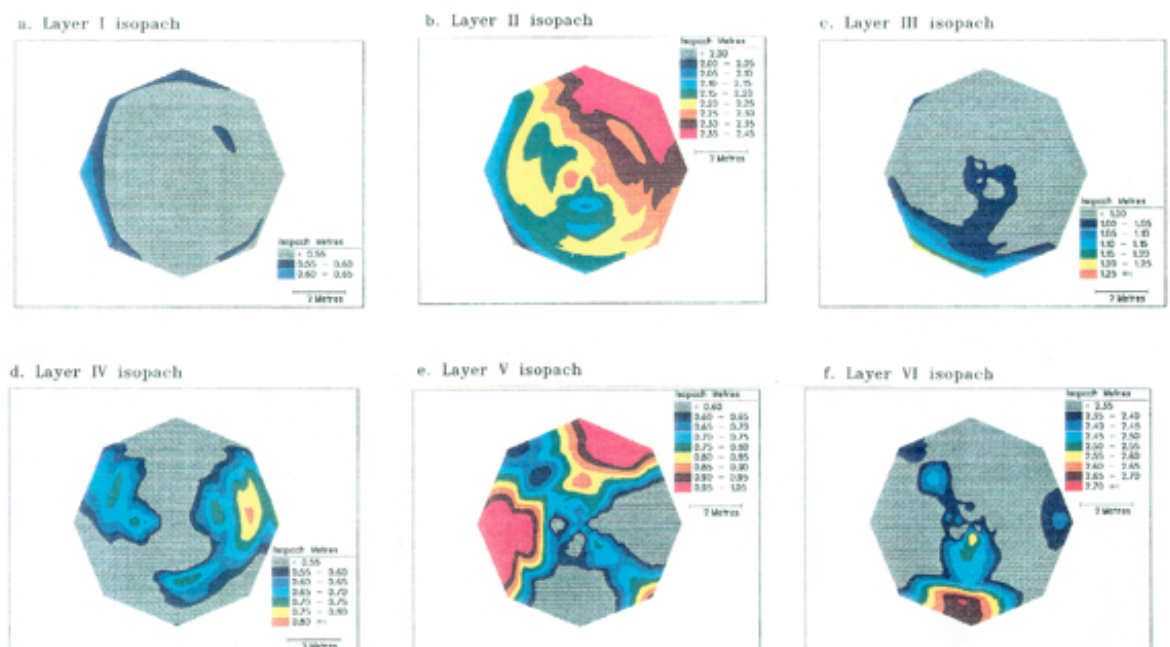


Figure 28: Isopachyte results for six layers into the sub-seabed. Source: From Guigné et al., 1991 and from Pike, 1998's thesis.

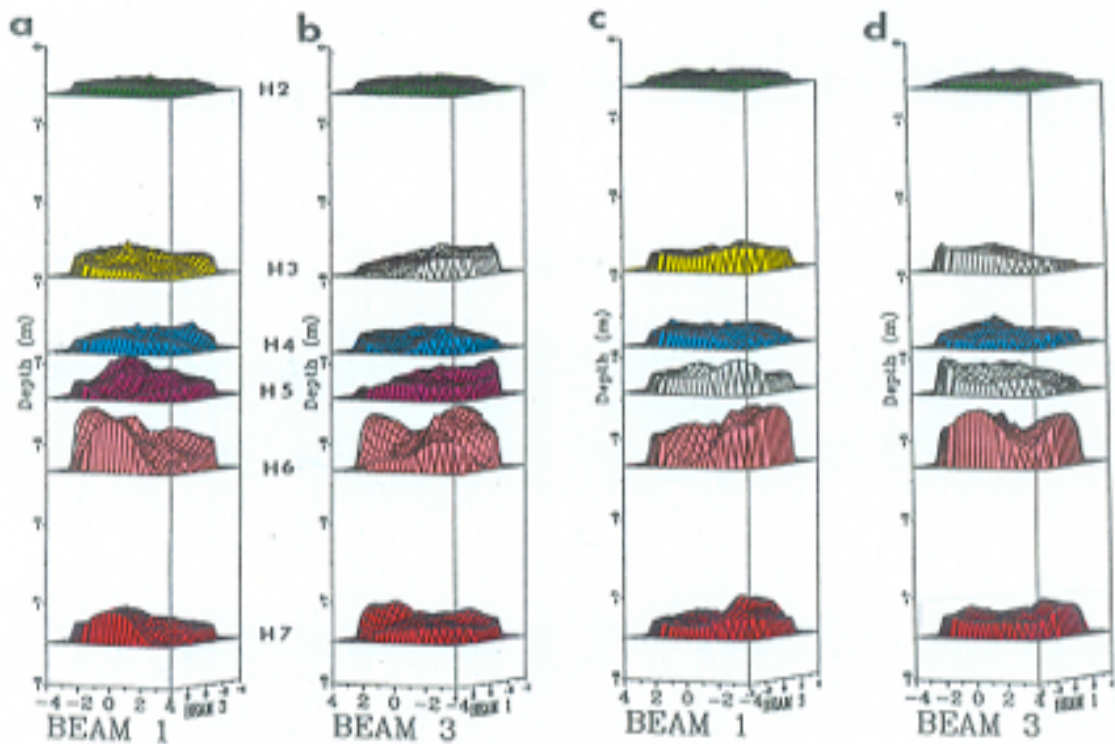


Figure 29: 3D rotated presentation of the data isopachs. Source: From Guigné et al., 1991 and from Pike, 1998's thesis.

The final answer product that was delivered correlated well between datasets—the ASI seismic acquired data related to the boreholes and CPTs descriptions and values even though this was deemed a difficult, complex, and inhomogeneous site involving coarse gravels and broken bedrock. (see Figures 30 and 31).

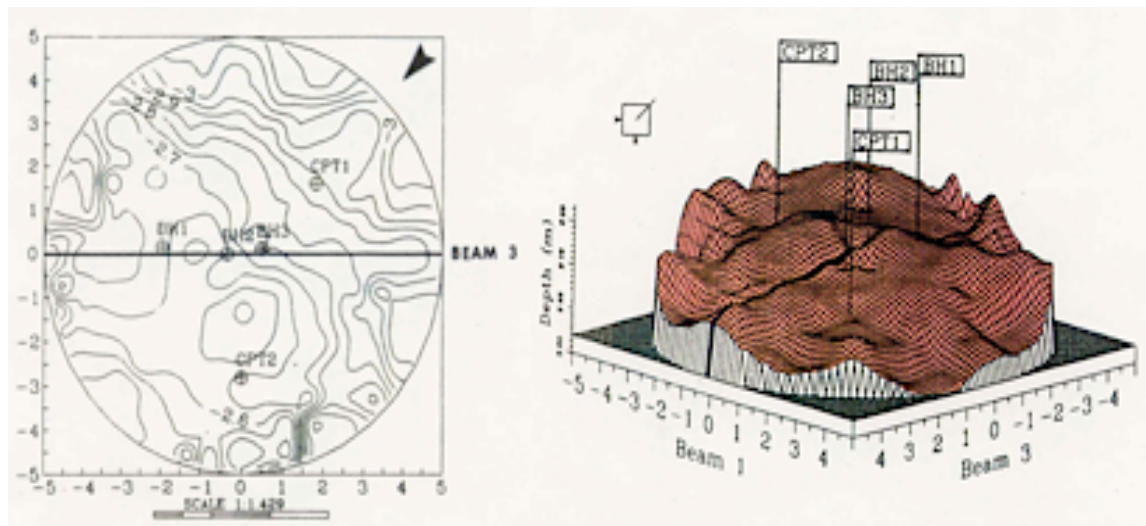


Figure 30: Presents a sketch and overlain bathymetry of the data acquisition configuration, the four data acquisition beams and the co-location of two boreholes and four CPT tests. Source: From Guigné et al., 1991 and from Pike, 1998's thesis.

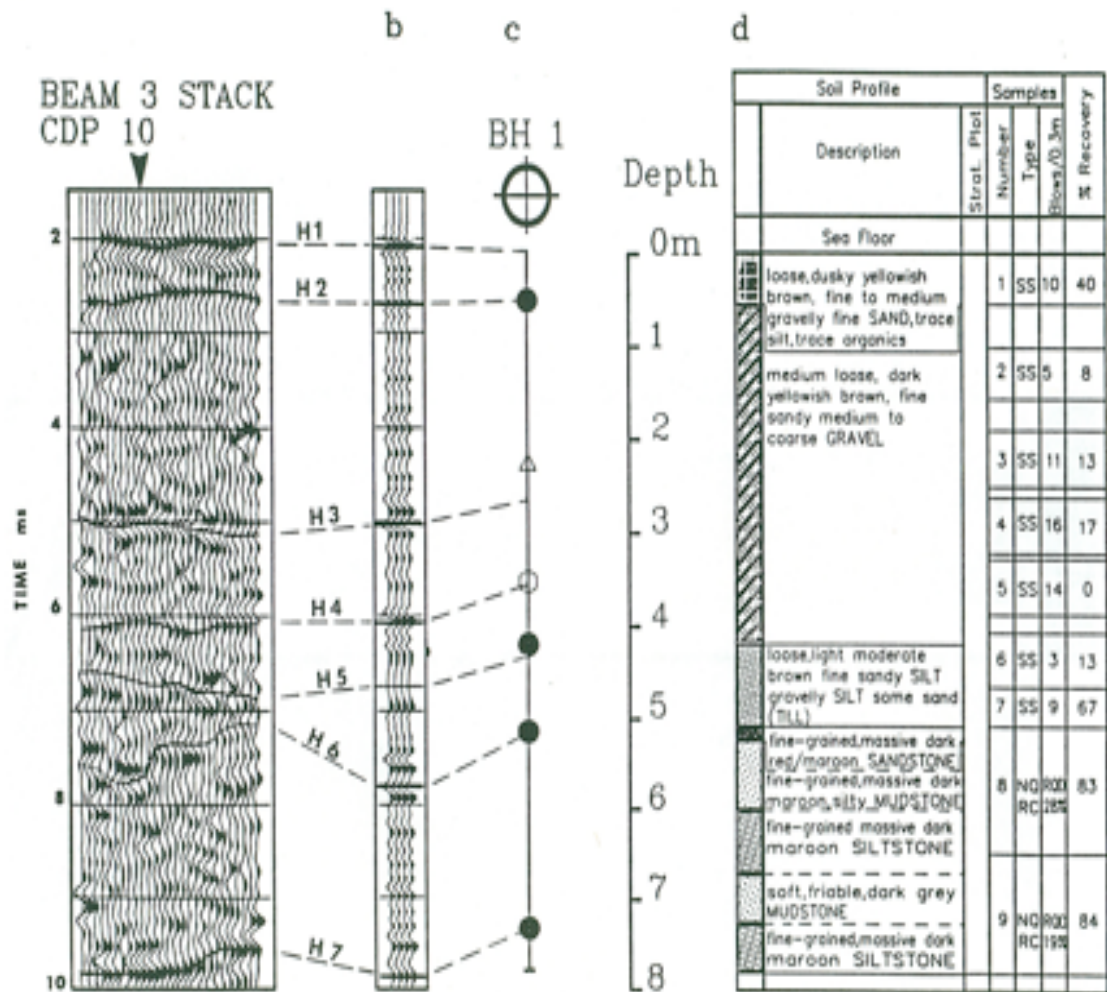


Figure 31: a) Brute stack for Beam 3 showing horizon picks; b) Normal incidence trace(replicated four times) coincident with CPD10; c) Borehole 1 showing identified stratigraphy, black circles; d) Portion of log for Borehole 1. Dashed lines between a, b and c, indicate correlations between CDP horizons, normal incidence events and borehole stratigraphy. Source: From Guigné et al., 1991 and from Pike, 1998's thesis.

3.4 The Next Generation: The Acoustic Corer™

The early 1991 prototype ASI embodiment led the way to various offshore seabed and laboratory-based investigations from 1992 to 2005 to better understand the acoustic complexities of buried targets and to capture in a discrete manner the diffuse nature of these targets within the more specular layer by layer nature of geological formations. In 2006, a more sophisticated ASI engineering development was initiated. This development, called the PanGeo Subsea Inc. "Acoustic Corer™," consisted of engineering sonar hardware and data collection scripts, advanced digital data processing, and interpretation protocols to acquire both the specular and non-specular responses of the first 30 meters in complex sub-seabeds. The emphasis in processing the data was to fuse it with other available geotechnical and geological datasets.

What is important is that there is an extensive data interrogation and fusion of various acquisition methods and signal processes, which directly stitches a link between the raw data and interpretable datasets. The instrumentation platform illustrated in Figure 32 consists of the following:

- i) A parametric transducer and receiver system,
 - Primary Frequency 100kHz with a set of secondary frequencies at 5,6,10,12 ,and 15 kHz?
- ii) A High Frequency Chirp Source with a range of 4.5-12.5 kHz (7.5 kHz mean)
 - Duty cycle (DC) \approx 10% (-20dB)
 - Directivity Index (DI) \approx 5dB
 - Effective SPL = Peak – DI – DC = 190 - 5 – 20 = 165dB //uPa-m
- iii) A Low Frequency Chirp Source with a range of 2.0-6.5 kHz (3.6 kHz mean)
 - Duty Cycle (DC) \approx 10% (-20dB)
 - Directivity Index (DI) \approx 6dB
 - Effective SPL = Peak – DI – DC = 195 - 6 – 20 = 169dB //uPa-m
- iv) A hydrophone array

The early 1991 prototype ASI embodiment led the way to a more sophisticated ASI engineering development in 2006. This development, called the PanGeo Subsea Inc. “Acoustic Corer™,” consisted of engineering precision sonar hardware and data collection scripts, advanced digital data processing, and interpretation of processed acoustic data fused with other available geotechnical and geological datasets.

Acoustic Corer Sonar Package

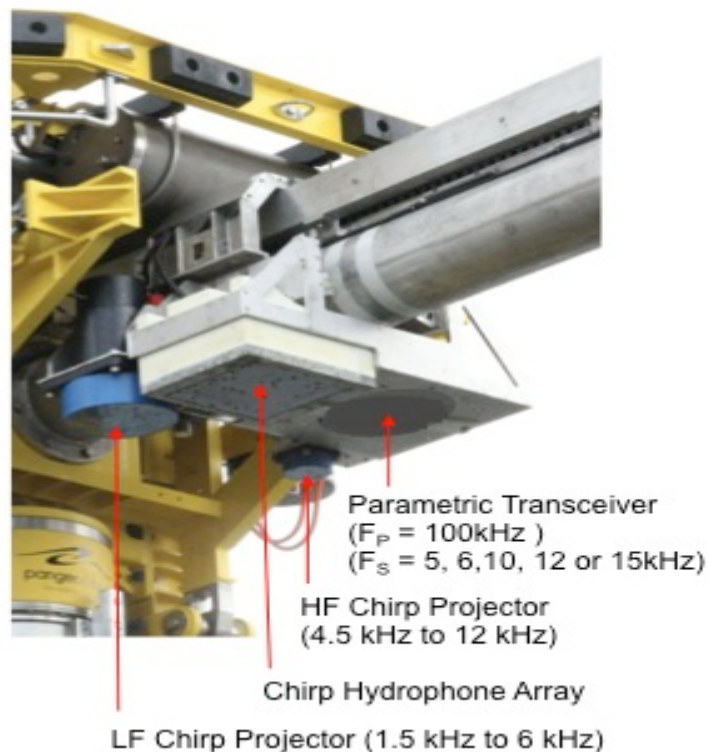


Figure 32: Sonar package for the PanGeo Subsea Inc. Acoustic Corer™ Source: PanGeo Subsea Inc. marketing archive 2011

Figures 33 and 34 introduce the PanGeo Subsea platform on which the acoustics are carried out to form a distinct transmitting and receiving array⁴. This embodiment of the ASI was engineered to acquire multi-aspect and multi-fold dense data in a twelve-meter diameter down to a depth of 30 to 40 meters.

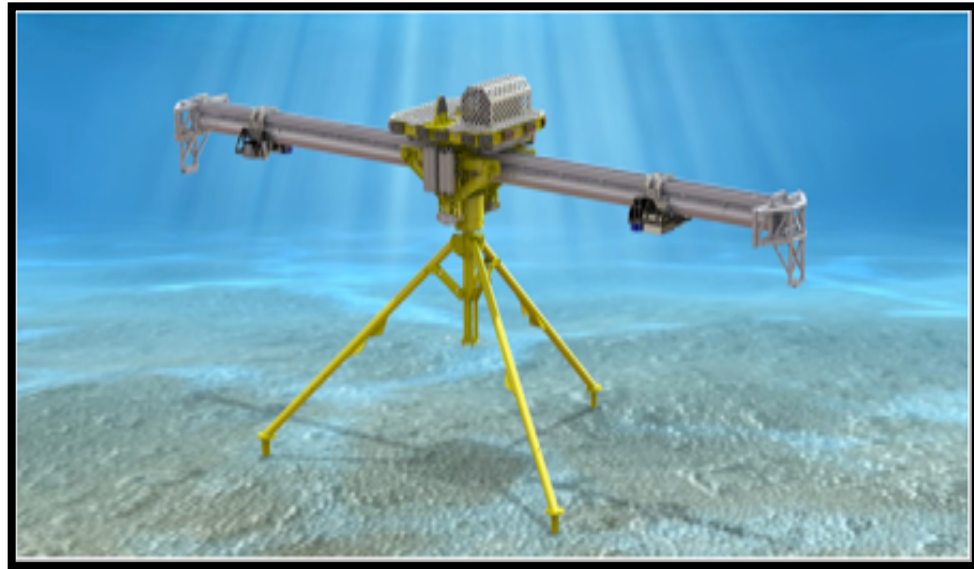


Figure 33: Illustration of the Acoustic Corer™ platform, opened up and sitting on the seabed. From a mechanical embodiment context, the Acoustic Corer™ is a mechanical system consisting of a tripod, two antipodal booms (arms) that rotate about the central pivot, and on each boom an independently moving instrumentation platform. Source: PanGeo Subsea Inc. marketing archive 2011

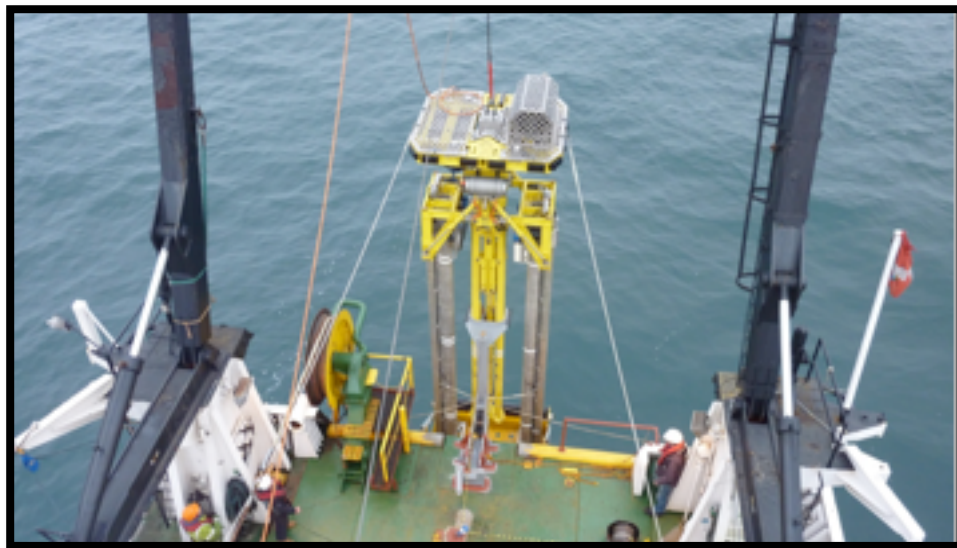


Figure 34: Photograph of the unit being deployed off a survey vessel in the North Sea in 2011. Source: Photo from PanGeo Subsea Inc. marketing materials, 2011.

⁴ The engineering development of PanGeo Subsea Inc.'s Acoustic Corer™ involved a dedicated team led by G. Openshaw, G. Dinn, T. McKeever, M. Hicks, and D. Hicks, with software engineering support led by R. Charron, S. Bromley, and C. Bulger. Data interpretation was undertaken by I. McDermott. Financial sponsorship was from Energy Ventures, Limerock Ventures, and Chevron Technology Investments

3.5 Strength Is With Coherent Summation

The strength of acoustic sub-seabed interrogations is founded on its pursuit to capture coherent summation (i.e. focusing) of the backscattered wavefield. The focusing methodology relies on straight-ray geometrical approximation to capture discrete heterogeneity diffuse scattering. That is, for each voxel (small computational volume) the total backscattered contribution is calculated, where each transducer-receiver pair observes the platform location's specific total travel time to-and-from the scattering volume.

If an actual scatterer existed, such as a boulder within the small volume under investigation, the contribution would be high due to coherent summation. On the other hand, if no scatterer (boulder) was present within the specified volume, the total contribution would register values that are very low due to incoherent summation. Moreover, because the size of the (synthetic) aperture is much larger than the wavelength, the scattering at 30m or less would have to occur within the near-field of the source/receiver antennas.

The entire volume rendering/interrogating process involves successive interrogations of individual resolution cells thus providing multiple confirmation of a target's presence. The answer product derived from using such densely collected and beam-formed synthetic aperture sonar (SAS) application delivers a volumetric acoustic core product as illustrated in Figure 35.

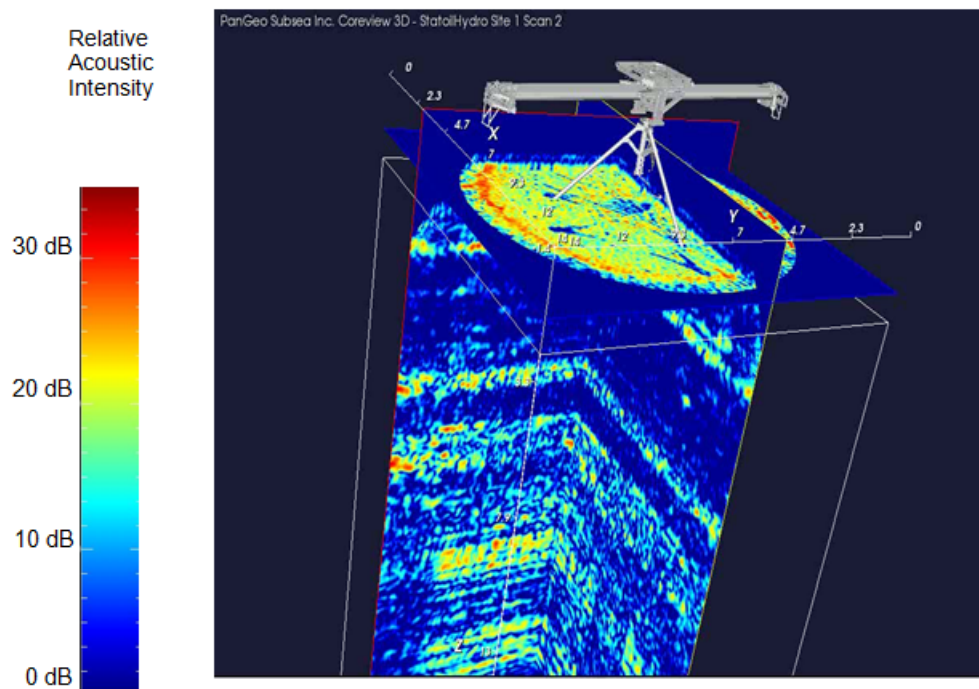


Figure 35: Typical acoustic core product after the SAS rendering is completed. Source: Statoil Ormen Lange Acoustic Corer trials in the Norwegian Sea; PanGeo Subsea Inc. marketing archive 2009, reproduced by permission.

3.6 Introducing The JYG-Cross

Appreciating the data collection strengths of multi-folding data as learnt from the Terenceville 1991 prototype trials, additional data acquisition scripts and processing routines were put in place in the Acoustic Corer™ to time migrate densely collected data along two lines. This data approach is referred to as the JYG-Cross data acquisition and

through this data acquisition plan more exact velocity profiles could be acquired at the interrogated site, which is an independent input in the rendering of the high frequency chirp data, to improve on the 'good of focus ' routines employed⁵.

Using the low frequency chirp, the JYG-Cross geometry of the acquisition simulates two 2D lines approximately 60° apart. The JYG-Cross data acquisition script consists of two 2D lines. In plan view the lines are approximately 60° apart and 30° from the nearest tripod leg. Each line consists of two radial and antipodal members where each member comprises a sequence of source or receiver platform locations.

The sweeps are generated at radial increments of 10cm; similarly, the receiver platform is radially shifted at 10cm increments since the low frequency chirp is being used. Figure 36 presents the configuration of the transmitter locations and receivers (where the source is shown as a solid dot and the receiver elements are as solid triangles). Figure 37 illustrates its placement in view of the geometry of the Acoustic Corer™.

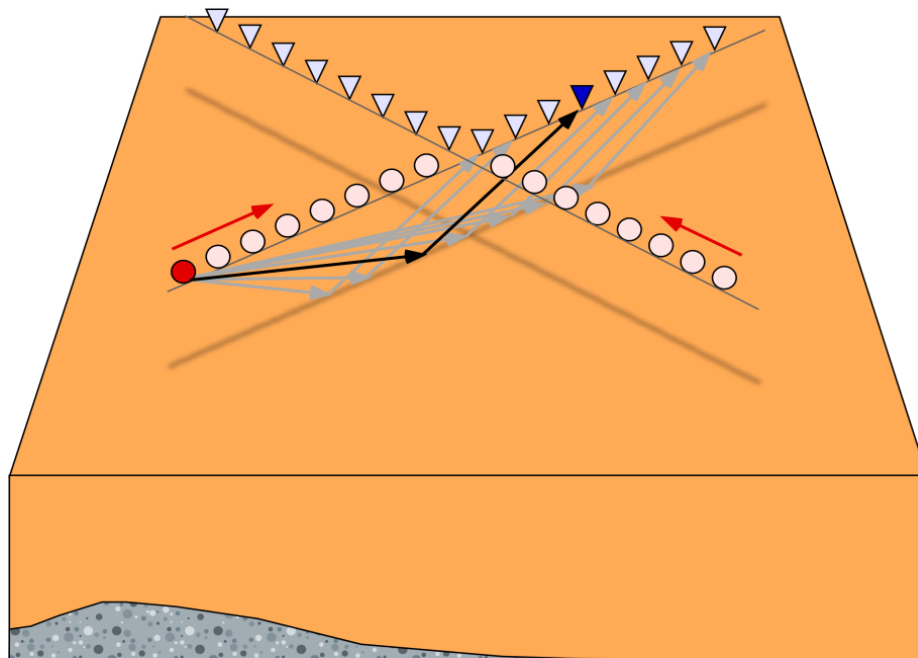


Figure 36: Pictorial view of the JYG-Cross configuration. Source: PanGeo Subsea Inc./ Guigné internal processing documentation; PRC-02237-1 Acoustic Corer Protocol, March 2011.

Collecting this extra data set in this manner does mirror conventional seismic data migration protocols. However, the Acoustic Corer™'s very precise stationary location control, typically unattainable in sub-bottom profiling, allows for consideration to be given to the application of predictive deconvolution routines and potential applications of FK filtering on the data to suppress repetitive multiple echoes that can appear in the datasets.

A detailed signal analysis, QA/QC, is an important step in the processing sequence. Each shot and CMP gather is carefully analyzed for anomalously high amplitude traces as well as for anomalous spectral content distribution. For example, if a trace possesses

⁵ The acquisition design and processing was named after the author: JYG is Jacques Yves Guigné. Processing refinement and implementation of protocols involved A. Gogacz, R.Laidley and K. Welford

anomalously high amplitudes but the reflectivity is correct a simple scaling solves the issue; otherwise the trace is removed from the dataset. If the problem is identified to be spectrally motivated, bandpass, notch filters, or velocity filters are tested to determine if the issue is resolvable.

If traces or gathers require filtering, the filters are applied and the data is stored on the server for subsequent processing. However, if after stacking the noise persists, the data is pre or post stack filtered to remove the noise. A decision is made whether filtering is the optimal solution or whether stacking may least disturb the final cross-section.

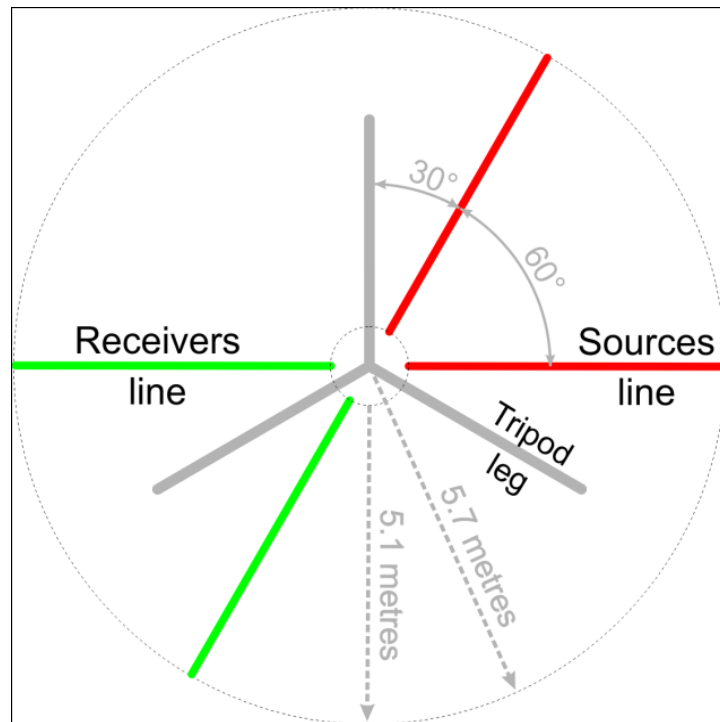


Figure 37: The JYG-Cross configuration in view of the Acoustic Corer™ where sweeps are generated along the red line and receivers are stationed along the green line . Source: PanGeo Subsea Inc./Guigné internal processing documentation; PRC-02237-1 Acoustic Corer Protocol, March 2011.

3.7 Applying Data Migration Routines

For each of the two lines, various data migration routines are considered and employed. Pre-stack migration is generally employed upfront along with regularly distributed common midpoints (CMP). Subsequently, each trace is assigned to its closest midpoint bin and the trace headers are updated to contain the CMP binning information.

As an example, along each line, the CMP bins are 5 cm apart, spanning a total length of 5.1 metres. The number of traces assigned to each CMP bin increases from the end of the CMP line toward the center and drops off at the same rate toward the other end. Maximal fold occurs at the central bin and includes 51 traces.

The collection of traces that fall within each bin is commonly referred to as a CMP (Figures 38 and 39 illustrate the CMP).

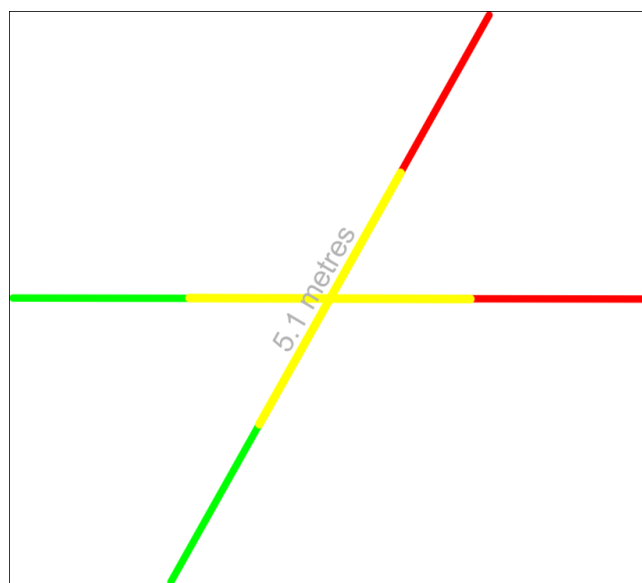


Figure 38: The line of CMP bins is shown in yellow with the acquisition lines shown in green and red. Source: PanGeo Subsea Inc./Guigné internal processing documentation; PRC-02237-1 Acoustic Corer Protocol, March 2011.

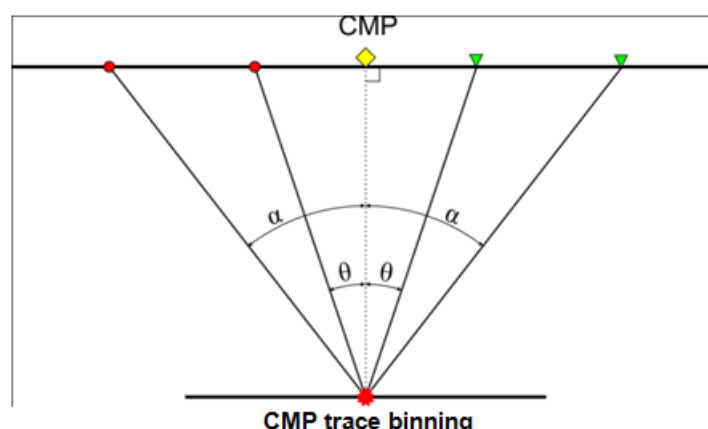


Figure 39: CMP trace binning. Source: PanGeo Subsea Inc./Guigné internal processing documentation; PRC-02237-1 Acoustic Corer Protocol, March 2011.

3.8 Velocity Analysis

The velocity analysis module is used to derive a stacking velocity model, subsequently used to convert the multifold JYG-Cross data to a “normal incidence” profile. This step is most time consuming and crucial to the entire processing sequence. The outcome of this process is a stacking velocity model that is later converted to an interval velocity model via Dix’s equation and a 1D velocity-depth model is hence derived (see Yilmaz (2001) for basic explanations on seismic analysis). For each line the velocity analysis is completed independently. To carry out the velocity analysis, semblance plots, multiplicity of constant velocity gathers (constant velocity NMO corrected gathers) at selected CMPs as well as a multiplicity of constant velocity stacks (constant velocity NMO corrected and stacked CMP gathers) are simultaneously analyzed. Based on semblance and constant velocity panels a decision is made on the compilation of a two-way-travel-time and CMP dependent stacking velocity model. Figure 40 presents an example of a semblance analysis plot.

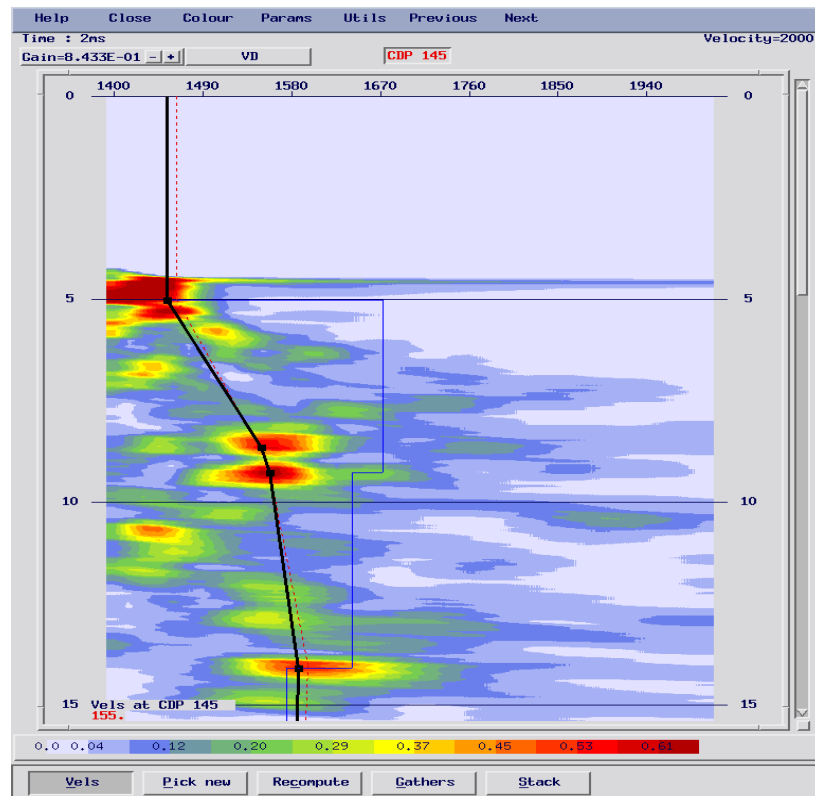


Figure 40: Semblance analysis. Source: PanGeo Subsea Inc./Guigné internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.

Because the acquisition reference datum is generally parallel to the seafloor and the observed stratigraphic boundaries are sub-parallel to the acquisition datum, no dip dependent correction is required. As such, in the CMP gathers the specular reflections follow mostly time axis symmetric hyperbolic trajectories. Figures 41 and 42 present examples of constant velocity CMP gathers and constant velocity stacks.

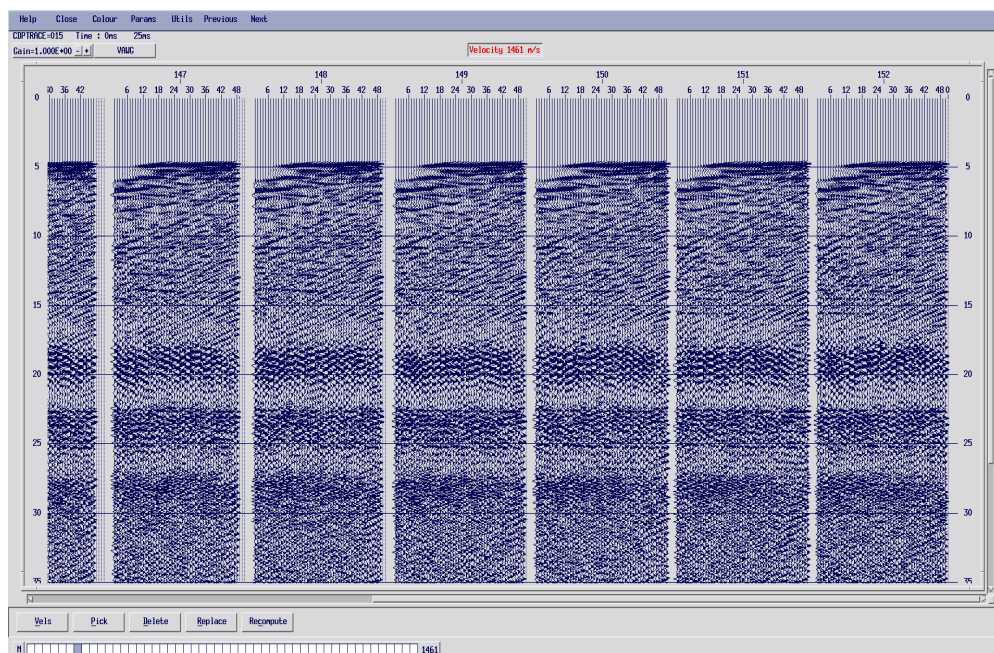


Figure 41: Constant velocity CMP gathers. Source: PanGeo Subsea Inc./Guigné /internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.

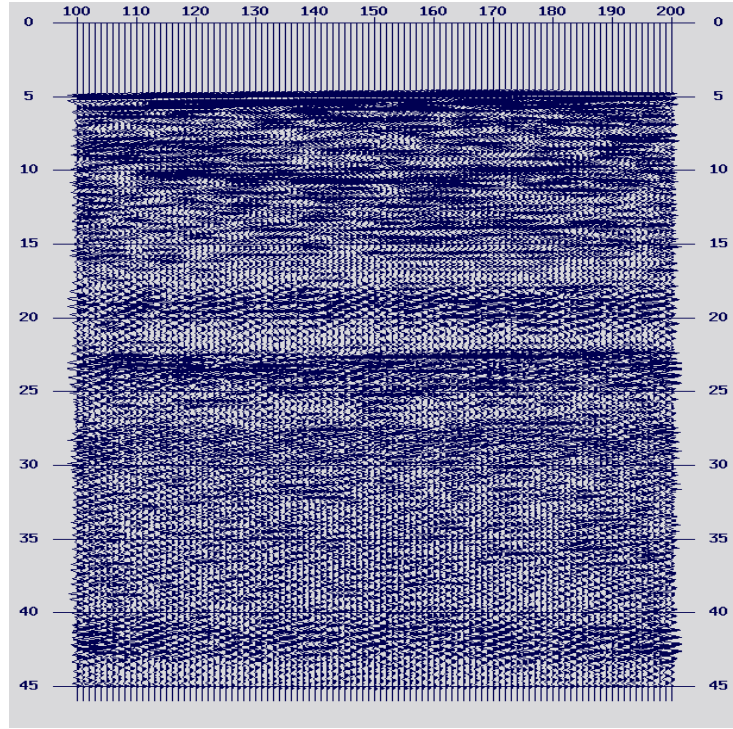


Figure 42: Constant velocity stacks. Source: PanGeo Subsea Inc./Guigné internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.

Once the stacking velocity model for each line is obtained, it is used to flatten the hyperbolic reflection trajectories in each CMP gather. The flattening is datumed with respect to the zero-offset trace as dictated by the following normal move-out (NMO) equation,

$$\Delta\tau_{NMO}(x) = \tau(x) - \tau(0)$$

where $\tau(x)$ is the two-way-travel-time to a specified depth point on a reflector, with source to receiver offset of x units apart and obeying Snell's Law of reflection at the interface. The equation for $\tau(x)$ can be obtained using geometric relationship,

$$\tau^2(x) = \tau^2(0) + \frac{x^2}{v^2}$$

with v denoting the layer interval velocity. Using Binomial Theorem, to first-order accuracy, the move-out correction $\Delta\tau_{NMO}(x)$ can be expressed as,

$$\Delta\tau_{NMO}(x) \approx \frac{x^2}{2\tau(0) v^2}$$

In a horizontally stratified medium and where the offset is smaller than the reflector depth the velocity in the above equation can be replaced with the RMS velocity. The NMO correction is a nonlinear operation that, upon flattening, proportionately stretches the wavelet with increasing offset.

To avoid spuriously stretched signals a maximal 70% NMO stretch mute is applied to

each NMO corrected CMP gather. Following NMO correction, each CMP gather is stacked. That is, all the traces comprising a specific CMP gather are added together and divided by the fold of the gather; this ensures normalization.

3.9 Dealing With Interference and Multiple Echo Suppression

A key issue to resolve when acquiring data in very shallow water is the effect of associated multiple bounces. When surveying at shallow sites, generally less than 20 meters, sea-surface shallow water multiples arrive at the receivers well within the profiling depth of interest. Digital advanced processing techniques can now be used to suppress the overprint of the multiples onto the primary reflectivity (Alessandrini et al., 1989).

Given the lateral irregularity of the multiples in response to wave action, predictive deconvolution is the most suitable technique for the suppression of these influenced multiples. This can be applied to the stacked data. The reflection mechanisms typically generate triplet of multiples, which can be observed in the processed data.

Figures 43 and 44 illustrate the sea-surface multiple bounces and their arrivals along with a data example. Prediction lag and operator length parameters are used to set the predictive deconvolution operators. Figure 45 presents a predictive deconvolution application for suppression of multiples.

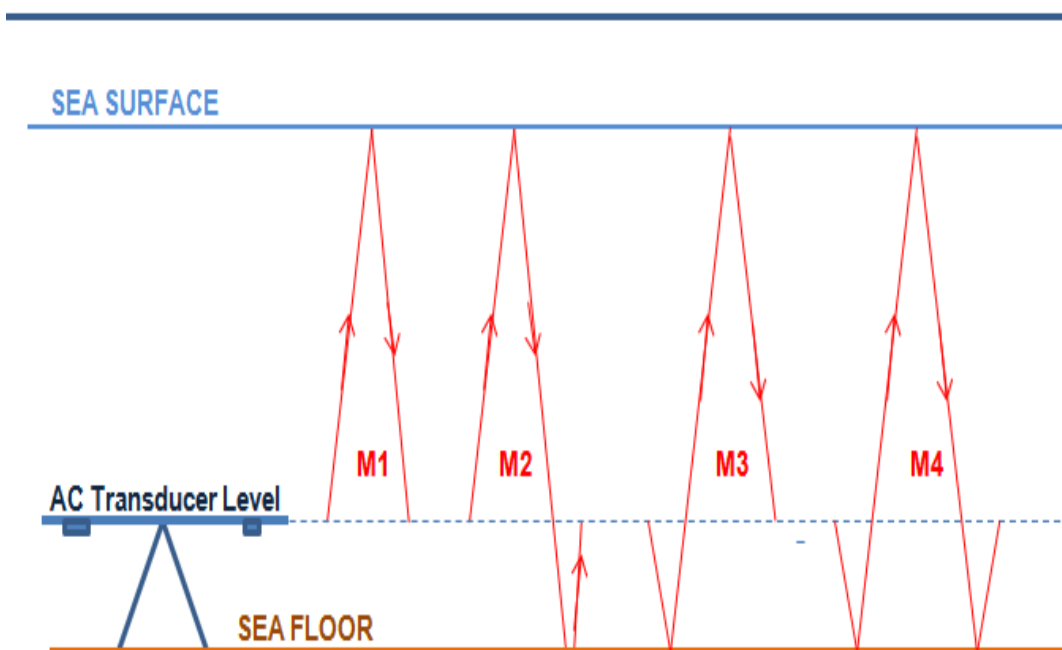


Figure 43: Sea-surface induced multiples. Note multiples M2 and M3 are coincident. Source: PanGeo Subsea Inc./Guigné internal processing documentation; PRC-02237-1 Acoustic Corer Protocol, March 2011.

Further accentuation of sub-horizontal events and suppression of “jittery” multiples are achieved via running mix process (weighted averaging) by specifying the number of adjacent traces to be included in the averaging and the relative weight of each adjacent trace. A lateral smoothing process is performed which has the added benefit of increasing the S/N ratio for faint and laterally coherent events.

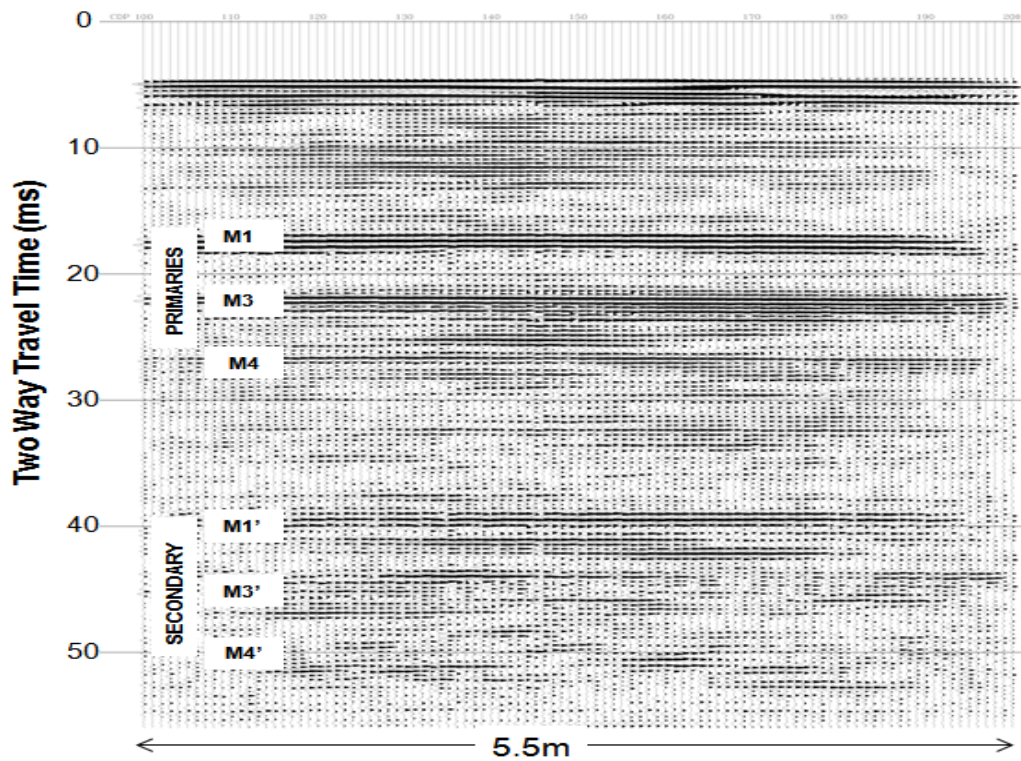


Figure 44: Example of shallow water multiples. Source: PanGeo Subsea Inc./ Guigné internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.

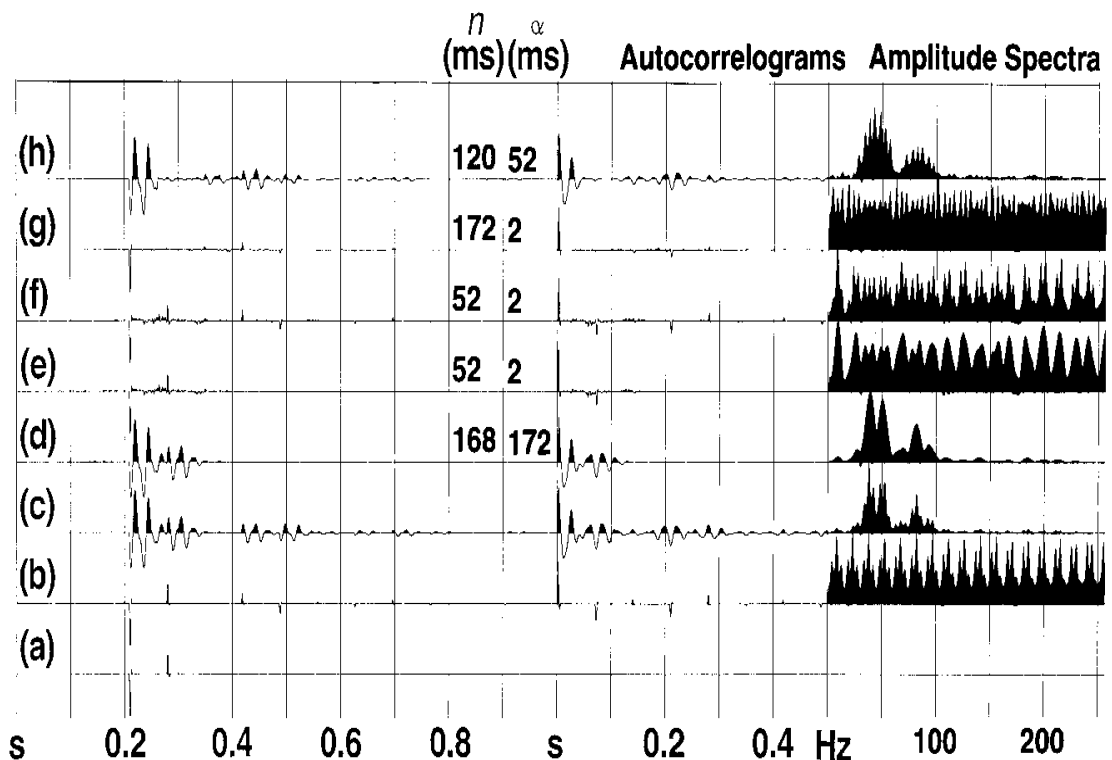


Figure 45: Predictive deconvolution for suppression of multiples: (a) reflectivity, (b) impulse response, (c) trace. Traces (d)-(h) are obtained by an application of predictive deconvolution using operator length n and prediction lag α . Source: PanGeo Subsea Inc./ Guigné internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.

3.10 Gains and Bandpass Applications

The last step in the JYG-Cross data processing consists of gain and bandpass applications as well as depth conversion of the data. The gain application is a trace-by-trace process and serves to balance the amplitudes across the entire time record. AGC is the most frequently used correction because amplitude information is not necessarily utilized for data interpretation (see Figure 46). Typically, stratigraphy and velocity information are noted to be relevant.

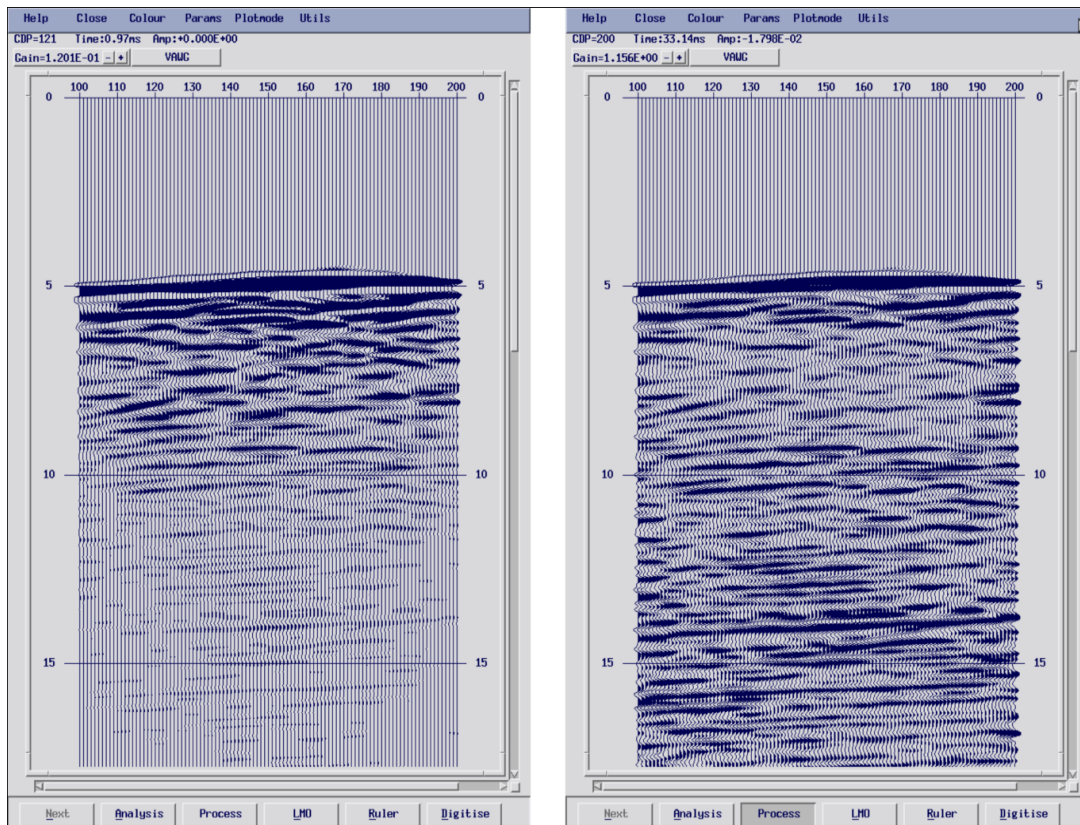


Figure 46: AGC comparison; the profile on the left is ungained; on the right is AGCed with an 8ms operator length. Source: PanGeo Subsea Inc./Guigné internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.

To eliminate any spurious energy, introduced during processing, at frequencies outside of the wavelet bandwidth the profiles were bandpass filtered with a zero-phase Butterworth filter. Because the stratigraphic boundaries are subparallel to the line of acquisition and because of the geologically small scale of the Acoustic Corer™, a 1-dimensional velocity model is used to depth convert the processed data.

Generally, a small collection of representative CMPs is identified and an average RMS velocity model compiled. Using Dix's equation the model can be converted from an RMS to interval velocity model.

3.11 The Last Step In The JYG-Cross Processing

The last step in the interval velocity model compilation relates to the conversion from interval velocity as a function of two-way travel-time to interval velocity as a function of depth. The two-way travel-time to depth conversion is computed via integration,

$$d(t) = \int_0^t \frac{v(\tau)}{2} d\tau$$

where t is the two-way travel-time, d is the depth as a function of t , and v is the interval velocity model as a function t . The time-to-depth mapping of the profiles is converted from two-way travel-time to depth. At this stage the JYG-Cross data processing is deemed completed and the final profiles can be handed over to the interpreters.

3.12 Synthetic Aperture Sonar Renderings And Processing

The Acoustic Corer™ volume imaging is based on coherent summation of backscattered wavefield. The focusing methodology is based on straight-ray geometrical approximation to capture discrete heterogeneity diffuse scattering, the entire volume rendering/interrogating process proceeds by successively interrogating individual resolution cells (see Figure 47, which illustrates backscattered energy focusing).

From a computational viewpoint, this process is highly parallelizable and as such the data handling and rendering for the SAS routines are implemented by exploiting a dedicated onboard, massively parallel GPU architecture.

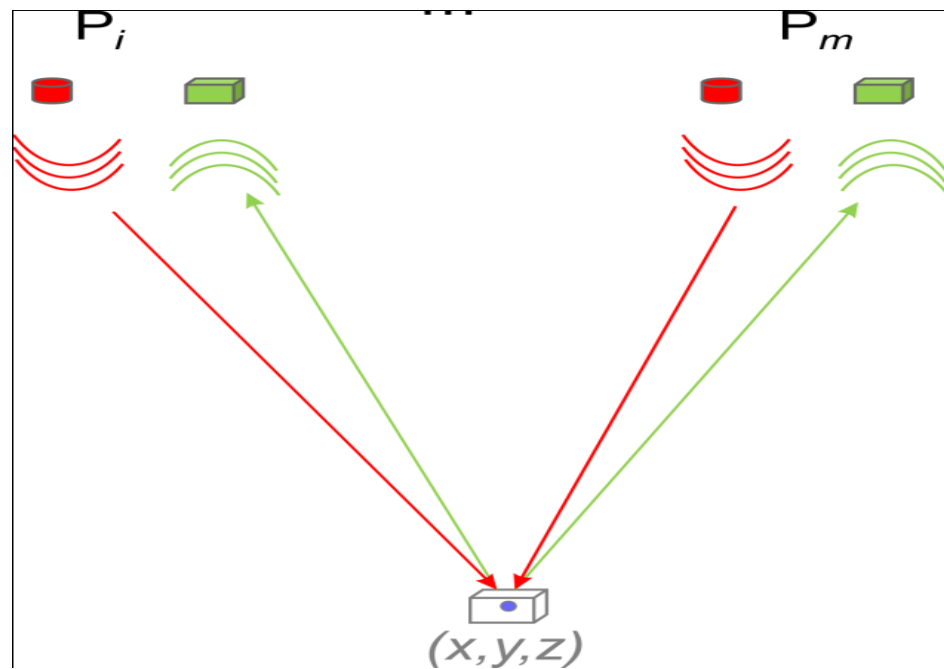


Figure 47: Backscattered energy focusing as “seen” at Pi and Pm platform locations
Source: PanGeo Subsea Inc./ Guigné internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.

3.13 Low and High Frequency Chirps

The acoustic transmissions involve a unique configuration of the low frequency and high frequency chirps; these are linearly frequency modulated chirps. The total duration of the chirp is 22 ms. As an option to aid in overcoming strong seabed returns and strong

energy broadcasts in the water column especially related to shallow water and their undesirable interactions, the chirp can be segmented into 10 chirplets, each 4.5 ms. The reconstruction of the desired 22-ms chirps is obtained via “stitching” together the chirplets with a specific overlap. The pulse compression type can either be match, mismatch, or none. Matched pulse compression consists of cross-correlation of the raw data with the stitched pulse (Guigné et al. [2012] patent describes in detail the chirp signal generations protocols for a discrete volumetric sonar method). Figure 48 presents and compares pulse compression. The mismatched pulse compression consists of filtering of raw data with a function, which after application to the pulse yields lower temporal side-lobes. The reduction of side-lobes is obtained at the expense of widening of the main-lobe. Hence, a compromise is established between main-lobe width and the relative amplitude of the side-lobes.

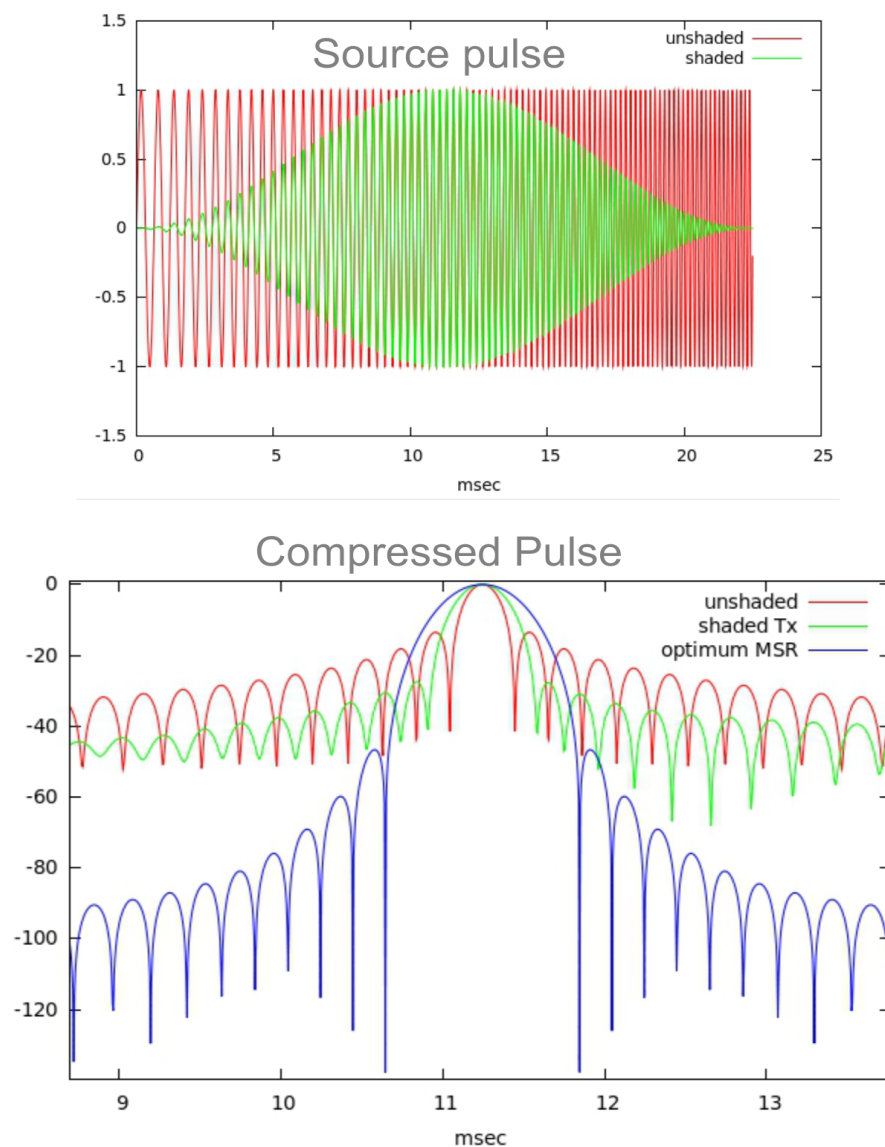


Figure 48: Pulse compression comparison. Source: PanGeo Subsea Inc./ Guigné internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.

3.14 Specifying the Size of the Receiver and Transmitter Cones

The parameters Θ_R and Θ_T specify the size of the receiver and transducer cones and thereby the specific transducer and receiver locations to be considered in the beam-former summation (refer to Figure 49). Based on experimental observations of transducer and receiver beam-patterns, optimal angular cone sizes are 30° for both the transducer and the receiver.

The shading parameter, if applied, can be either hard or Gaussian. Hard shading allows a trace into the summation based on whether the trace falls within the specified transducer and receiver cones. The Gaussian shading allows a trace into the summation based on whether the trace falls within the specified transducer and receiver cones with additional roll-off Gaussian scaling towards the edges of the cones. No shading ignores the transducer and receiver cones and allows all traces to enter the summation.

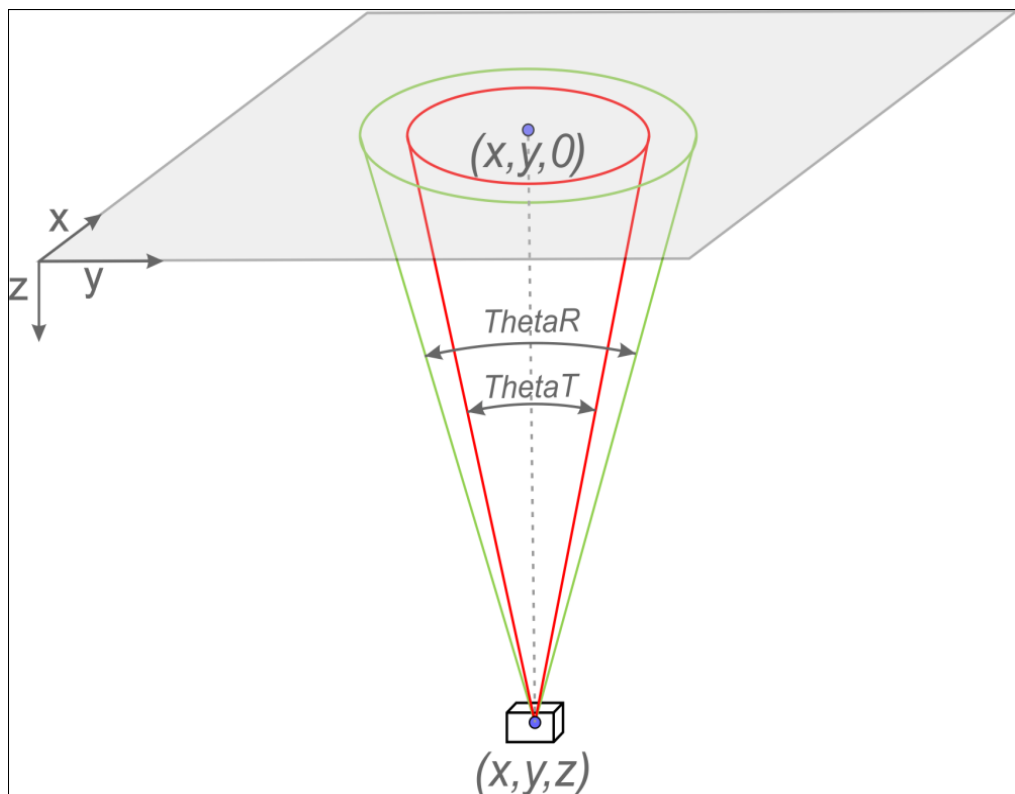


Figure 49: Angular transducer and receiver aperture limits (i.e. Θ_R and Θ_T) Source: PanGeo Subsea Inc./Guigné internal processing documentation, PRC-02237-1 Acoustic Corer Protocol, March 2011.

The summation option allows for analytic or incoherent beam-former summation. The analytic beam-forming summation algorithm, unlike conventional migration, consists of first mapping the recorded signals, $x(t)$, to their individual analytic extensions, that is,

$$x(t) \xrightarrow[\text{extension}]{\text{analytic}} x_a(t)$$

where the complex valued analytic extension, $x_a(t)$, is defined via convolution as,

$$x_a(t) = x(t) + j x(t) * \frac{1}{\pi t}$$

and subsequently performing the summation of the travel path corrected impulses in the complex domain. The resulting voxel value embodies the total target strength as well the envelope information of each summation contributor.

The incoherent summation option entails beamformer summation performed on the envelope of each recorded trace. This method of summation is particularly useful where the backscattered signal strength is high, in relation to background noise, and velocity model is not well constrained such as at times seen in shallow water, complex sub-seabed conditions.

3.15 Processing Flow Diagram

The following flow diagram (Figure 50) illustrates details on the way our data processing fuses the various datasets and analysis into a final construct for interpretation and delivery as an “answer product”⁶.

References Cited

- Alessandrini, B. & Gasperini, M. (1989). The deconvolution of a marine seismic source: an iterative approach. *Geophysics*, 780–784.
- Buogo, S. & Cannelli, G.B. 2002: Implosion of an underwater spark-generated bubble and acoustic energy evaluation using the Rayleigh model; *Journal of the Acoustical Society of America*, v. 111, 2594–2600.
- Inkpen, S.T., English, J., Pike, C.J., Guigné, J.Y., Guzzwell, J., Hunt P., Tuff, K. (1991). A three dimensional acoustic site surveying probe, OTC 91, *23rd Annual Offshore Technology Conf Procs*. Vol 1, Ppr OTC 6559, pp. 525-535.
- Mueller, C. 2005: The marine VHR 2.5-D seismic brute stack cube as a feasible tool for the low budget investigation and research. *Marine Geophysical Researches*, v. 26, pp. 197–206.
- Pike C. (1998). *High resolution acoustic investigations of sub-seabed soils: relationship of wavelet transformed acoustic image to soil properties and some geotechnical parameters*. Doctoral thesis, University of Wales, College of Bangor.
- Scheidhauer, M., Marillier, F., & Dupuy, D. (2005). Development of a system for 3D high-resolution seismic reflection profiling on lakes. *Marine Geophysical Researches*, v. 26, pp. 183–195.
- Yilmaz, O. (2001). Seismic data analysis. *Society of Exploration Geophysicists*, Tulsa, Oklahoma, pp. 20-27.

⁶ The flow diagram represents the collective efforts of J. Guigné, A. Gogacz, R. Laidley, Allison Brown and I. McDermott

Volume 2 – Associated And Related Patents/Publications By The Author

English, J., Inkpen, S., Guigné, J.Y. (1991). A New High Frequency Broadband Seismic Source. *Offshore Technology Conference*, Houston, Texas, May. pp.517-524.

Inkpen, S., Guigné, J.Y., Pike, C. (1991). A Three-dimensional Acoustic Site Surveying Probe. *Offshore Technology Conference*, Houston, Texas, May. pp. 525-534.

Guigné, J.Y. & Atkinson, Directional Response of a Vector Intensity Hydrophone Array. *Canadian Acoustics*.

Guigné, J.Y., Welford, J.K., Gogacz, A. & Clements, C. (2012). US Patent Application-Method for Accentuating Specular and Non-Specular Seismic Events from within Shallow Subsurface Rock Formations.

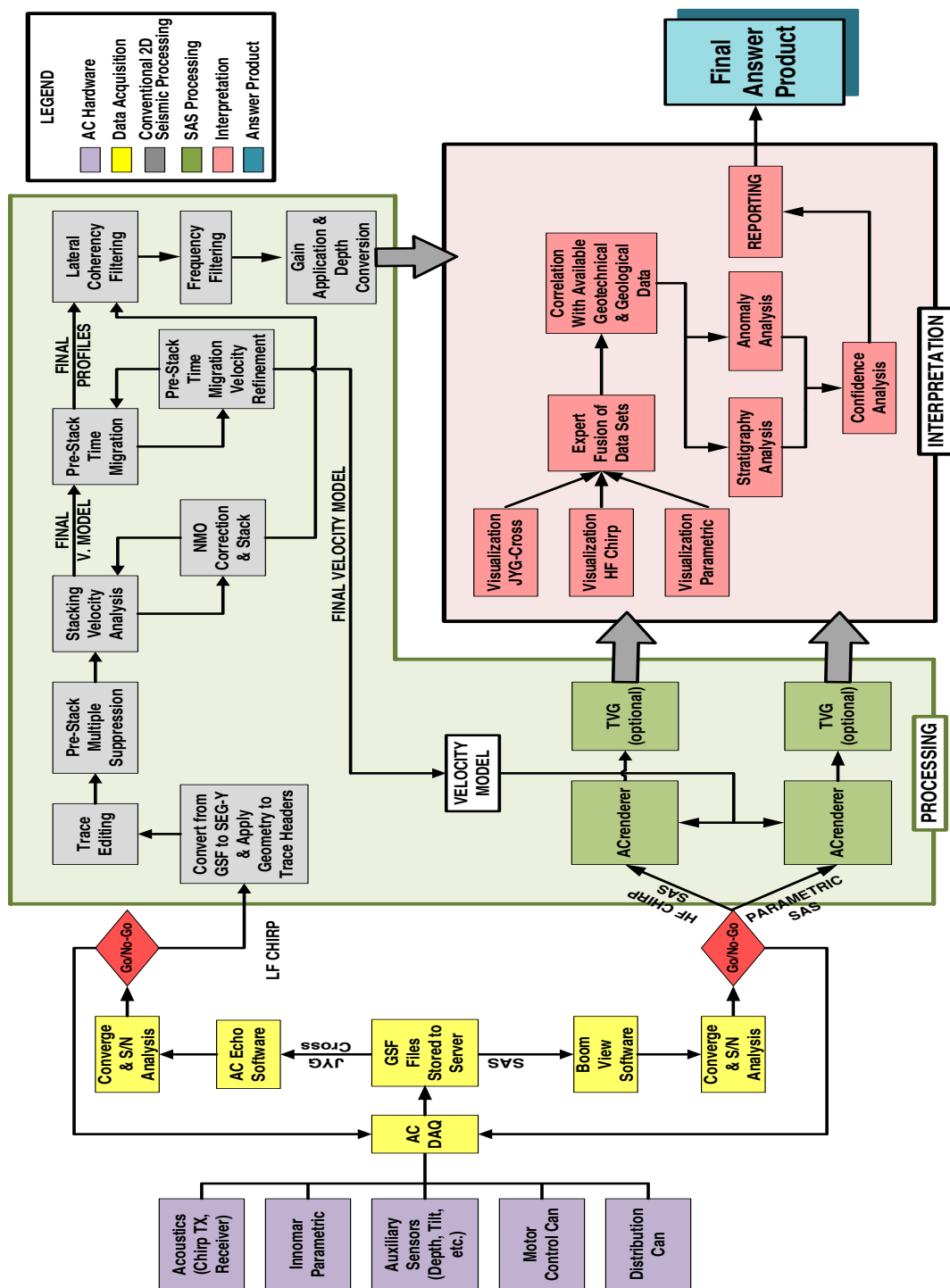


Figure 50: Processing flow. Source: PanGeo Subsea Inc./ Guigné, PRC-02237-1 Acoustic Corer Protocol, March 2011.

THE ANSWER PRODUCT

4.1 Classifying the Seabed Sediments in Terms of Specular and Non-Specular

JYG-Cross multifold data is acquired to enhance coherent specular reflections from stratigraphic layers within the ASI's data collection region of interest. As described in Chapter 3: Sections 3.6 and 3.7, this is achieved by collecting high resolution multifold data along two near orthogonal lines. Along each line, sources from a specific source location are recorded at a number of receiver locations and the process is repeated for multiple shot locations. A total of over 6,000 traces are typically collected. The resulting “shot gathers” are then processed using advanced seismic analysis techniques. (Guigné et al., 2010 and refer to patent Guigné et al., 2012). Figure 51 is an example of the multifold data from the JYG-Cross data acquisition.

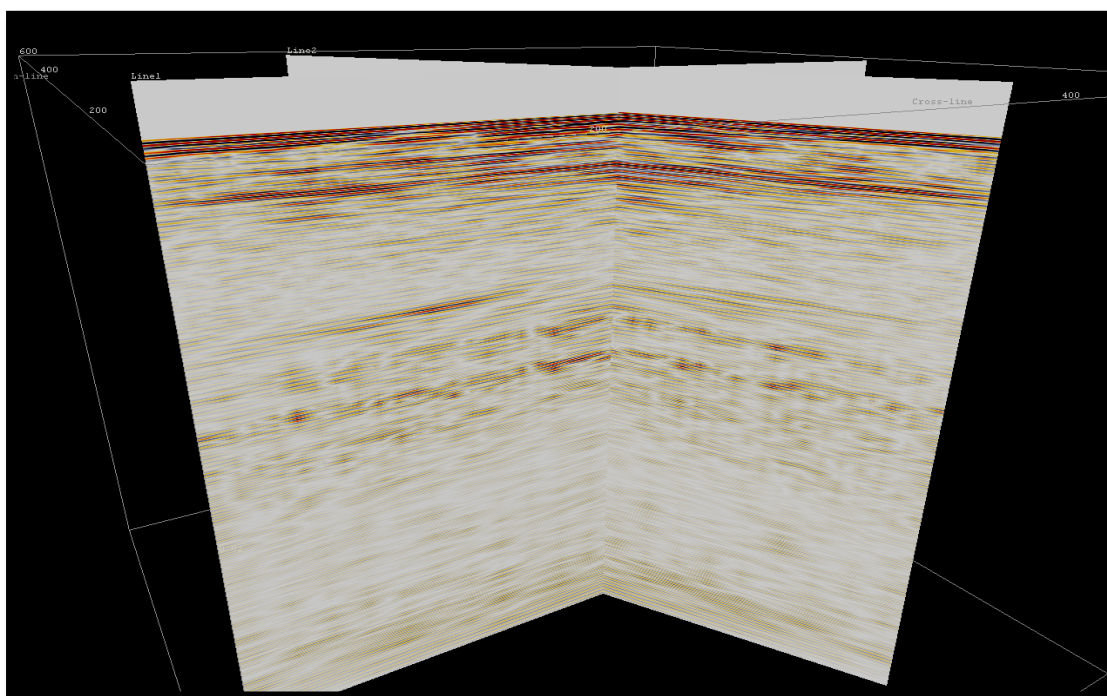


Figure 51: An example of the JYG-Cross multifold data. Source : PanGeo Subsea Inc. released materials, 2011.

In addition to improving the Signal-to-Noise of the dataset, the recorded offsets allow for velocity analysis to be performed, and allow the dip and strike of a sloping bed to be determined. Along each line, transmissions from a specific source location are recorded at multiple receiver locations and the process is repeated for a number of shot locations.

The resulting “shot gathers” are then processed using conventional seismic processing techniques, which include F-K filtering to remove interference reflections when working alongside structures such as an offshore caisson (the radiated acoustic energies reflect off these structural targets and tend to superimpose their response onto the seabed returns). The goal is to exploit the multiplicity of data through stacking to enhance coherent events and cancel out noise. Figure 52 is a layout installation plan view of the Dong Energy SIRI site (Danish North Sea) where an acoustic core was used as a

borehole replacement. In many circumstances when an offshore platform is in place, it is not possible to reacquire further physical borehole cores once an installation is present. In the case of the SIRI situation additional piles were being considered to reinforce the platform but the seabed risks had to be mitigated before such piling installations could be considered, hence an ASI investigation was deemed strategic and an appropriate substitute for a borehole.

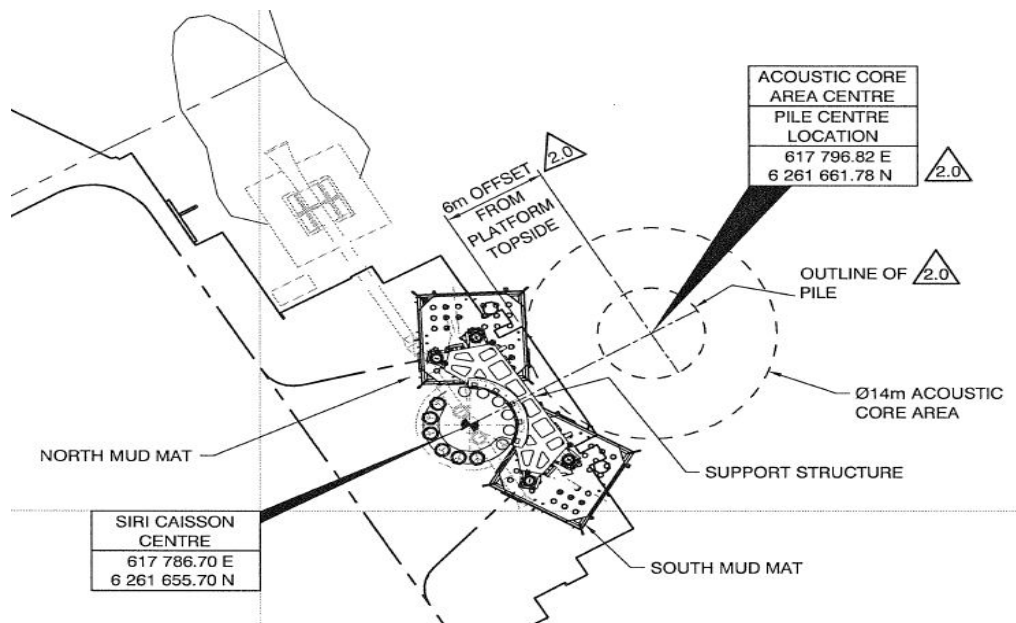


Figure 52: The SIRI caisson plan view with the location of the ASI acoustic core. Source: PanGeo Subsea Inc. SIRI related permitted marketing materials, 2010 and Guigné et al., 2010

JYG-Cross's data was acquired at the SIRI site and these data were processed to remove the reflective interference of the caisson using pre-stack F-K filtering (Guigné et al., 2010). This is presented in Figure 52. Once processed, an interpretation was made that revealed a gravel layer at 5m and a sloping stiff clay layer at 20m below seafloor (see Figure 54).

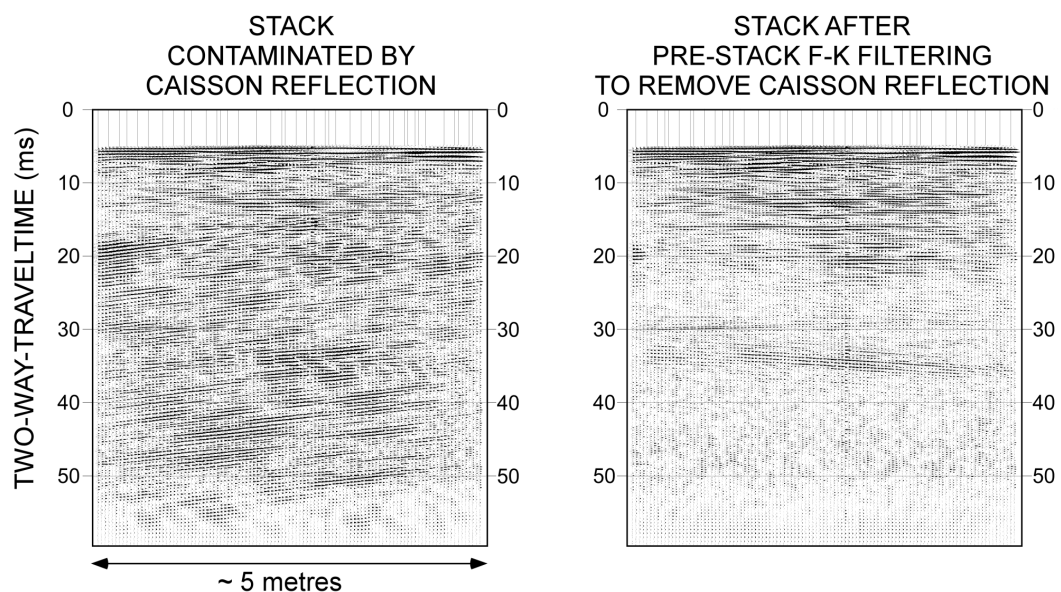


Figure 53: JYG-Cross processing of data where interference is present. Source: Guigné et al., 2010

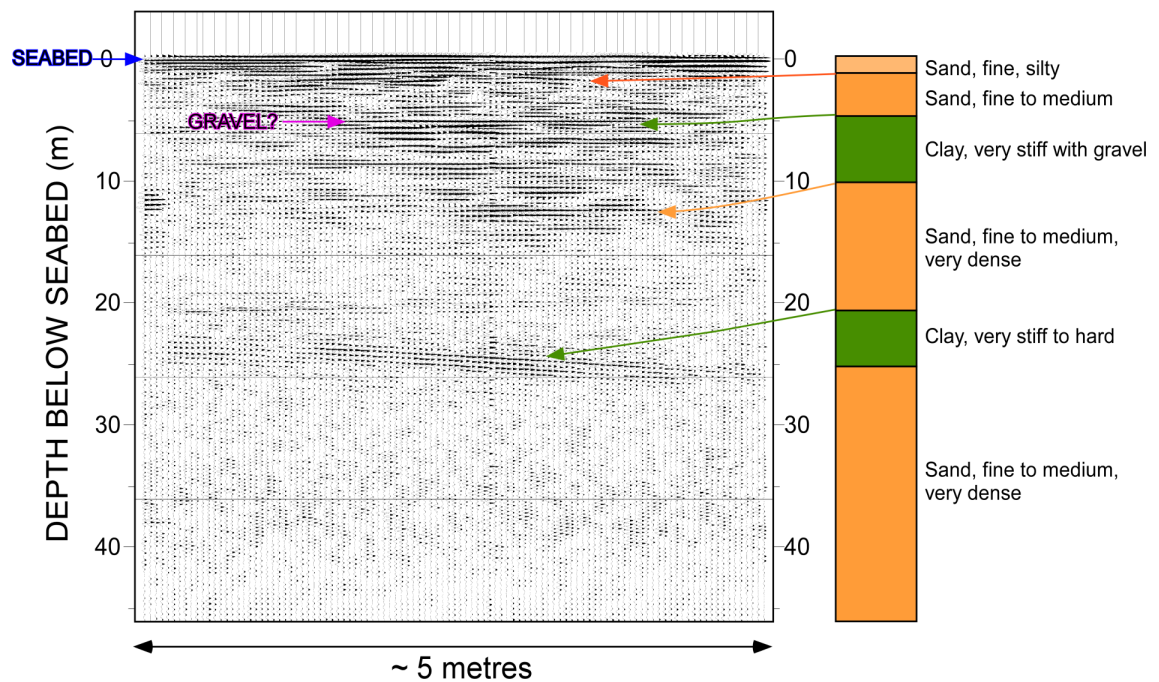


Figure 54: JYG-Cross processed SIRC data and interpretation. Source: Guigné et al., 2010

In the ASI protocols, synthetic aperture data (SAS) is acquired to accentuate non-specular targets or anomalies in the strata. This process (refer to Chapter 3: Sections 3.12, 3.13, and 3.14) involved acquiring approximately 20,000 discrete data points. These data were used to identify acoustic anomalies consistent with buried objects.

In the case of the SIRC site investigation there were six non-specular features noted. The anomaly shown in Figure 55 left panel (A) was most problematic for the client as it was positioned where the support caisson was to be placed. The anomaly is suggestive of a boulder of 0.55m in diameter and is located at a depth of 4.25m below seafloor. The anomalies are charted in terms of northing, easting, and depth of burial as shown in Figure 55, the diagram on the far right (B).

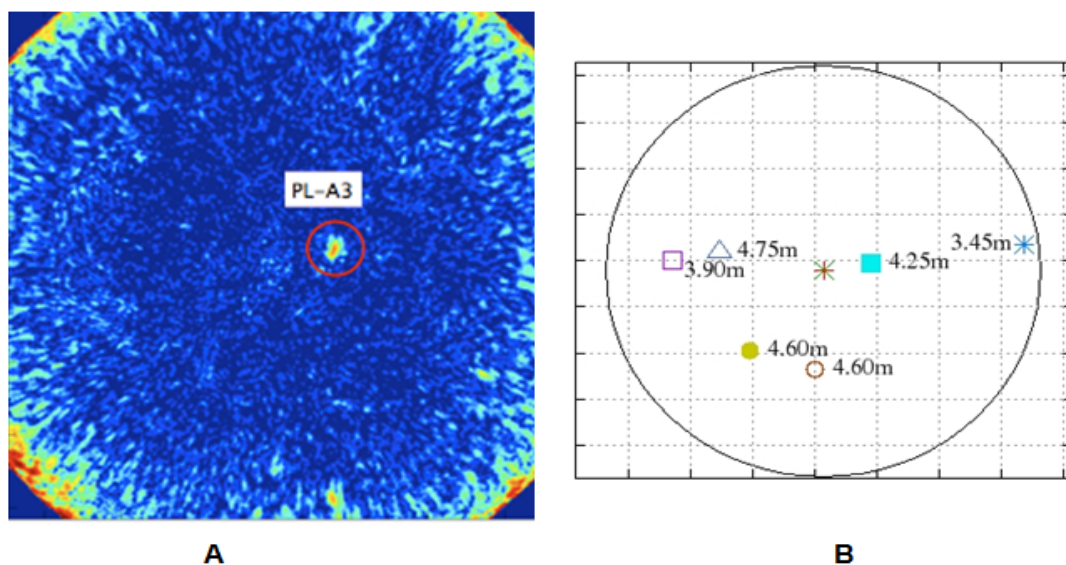


Figure 55: SIRC SAS High Frequency rendered anomaly at a depth of approx. 4.5 m in the seabed (Panel A is a horizontal 12 m dia. plane view at that depth) and geographic plot of the different anomalies detected (Panel B). Source: Guigné et al., 2010.

4.2 Anomaly Sizing

The ASI protocols and answer product are used to identify acoustic anomalies in the dataset, consistent with buried boulders. Since the data provides extremely high-resolution images, precise boulder locations to decimeter accuracy are possible. The SAS processing can be charted and have the coherency and signal strengths to detect boulders in highly reverberant gravelly sediments, something a conventional sub-bottom profiler cannot do. The high quality images make estimating the boulder size possible.

One of many techniques to consider when sizing anomalies is to plot the acoustic intensity along the longest axis of the anomaly, broken down into its x- and y-components. The lengths Δx and Δy are then measured as the distance between two points whose intensity are 3dB less than the peak. Where the -3dB value falls between two measured points, the distance is rounded up to avoid underestimating anomaly size (this is illustrated in Figure 56).

$$\text{Enclosing Circle Diameter of Anomaly} = \sqrt{\Delta x^2 + \Delta y^2}$$

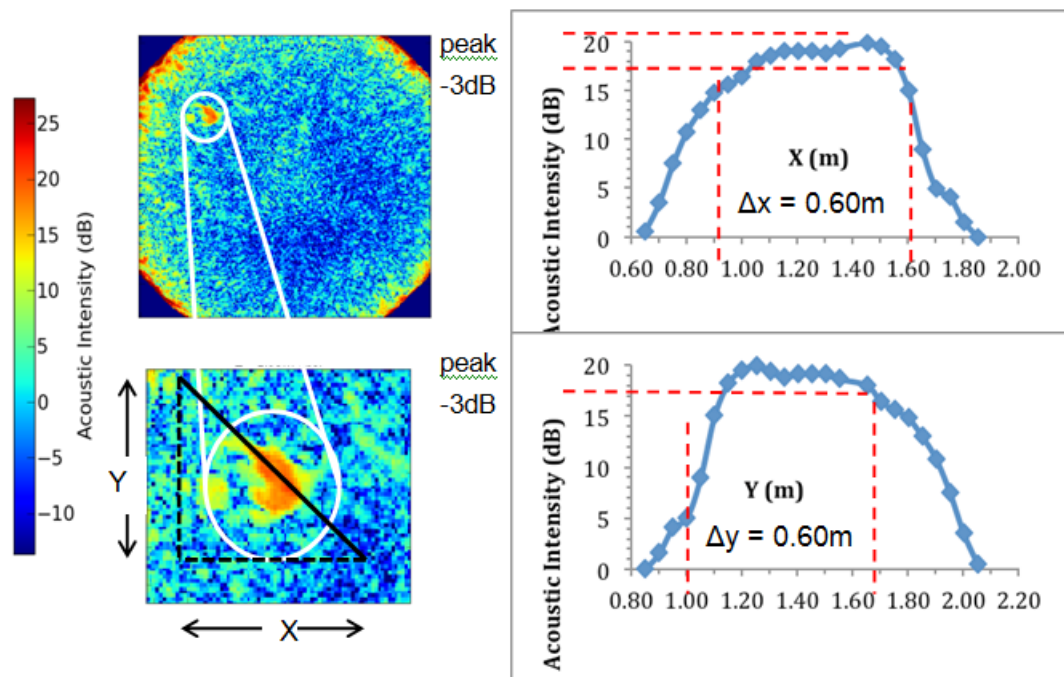


Figure 56: Composite illustration highlighting the sizing of a boulder anomaly by calculating the x and y dimension. Source : PanGeo Subsea Inc. AC data archive, 2011.

4.3 Boulder Identification

An important objective of interrogating the sub-seabed in a stationary manner is to image geotechnical anomalies and geo-hazards such as discontinuous layers and boulders. Because boulders tend to scatter acoustic energy the resulting imagery is a diffused response and in typical sub-bottom profiling will be noted as part of the background noise. With the ASI approach which uses multi-aspects views the returns become coherent and

part of the true seismic response thus raising these diffuse signals out of the noise background as coherent signals⁷.

As an example, the following boulder cluster located in a shallow water harbour and buried in a Till comprising sandy gravel was detected and rendered into an image at a depth of 2.2m below seafloor (see Figure 57). This cluster was subsequently retrieved using archaeological style recovery techniques and is also shown in Figure 57.

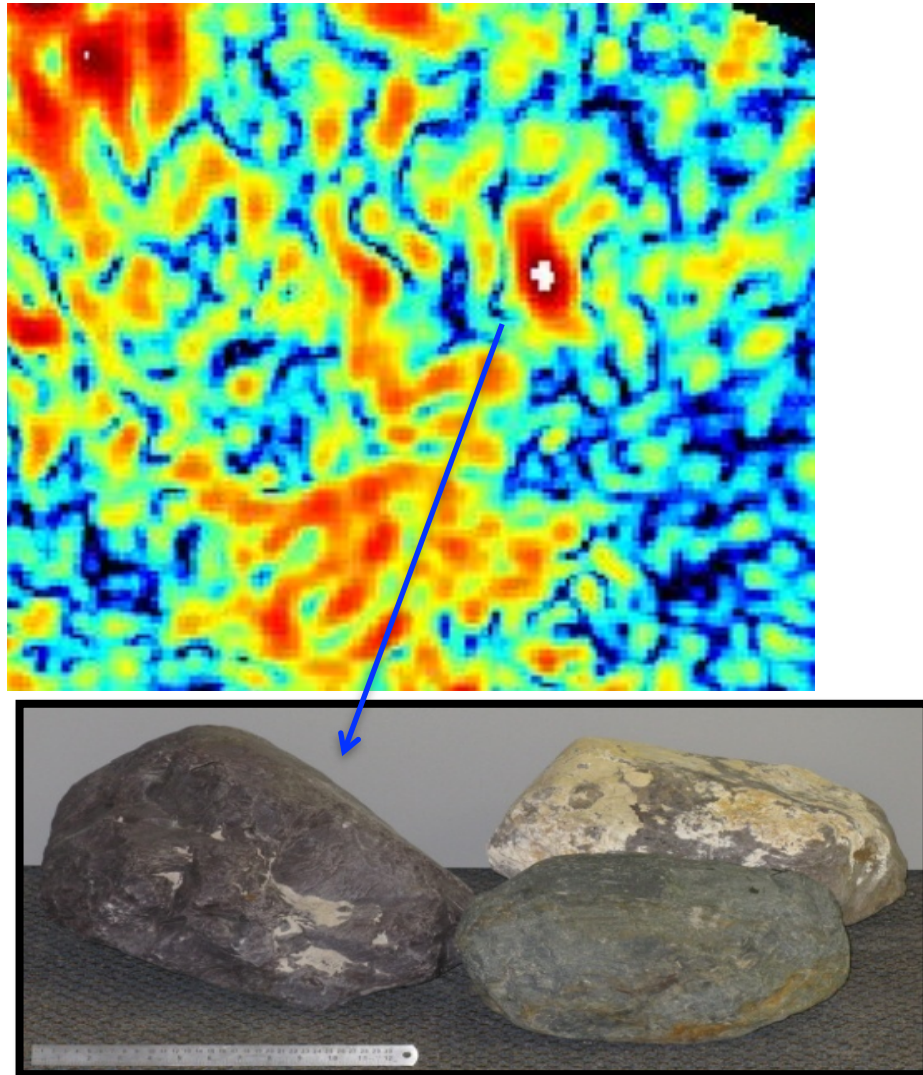


Figure 57: SAS rendered plan view horizontal data imagery slice (3m x 3m section) showing the boulder target and after excavation the cluster of boulders that were grouped together. Source: PanGeo Subsea Inc. AC data archive, 2011.

Another example of boulder detection is noted in Figure 58. The anomaly is suggestive of a boulder 0.5m in diameter. It is from a data set collected in the Baltic Sea. The boulder

⁷ The following example sections, imagery, descriptions and interpretations of boulders and sediment character are extracts from various Acoustic Core answer products and marketing materials delivered to various offshore installation clients by PanGeo Subsea Inc.'s geophysical team led by I. McDermott, A. Brown, R. Laidley with formal geoscience signing-off by J. Guigné

was located at 9.05m depth below seafloor in a marine late glacial clay unit. In the horizontal slice a series of small boulders are also seen.

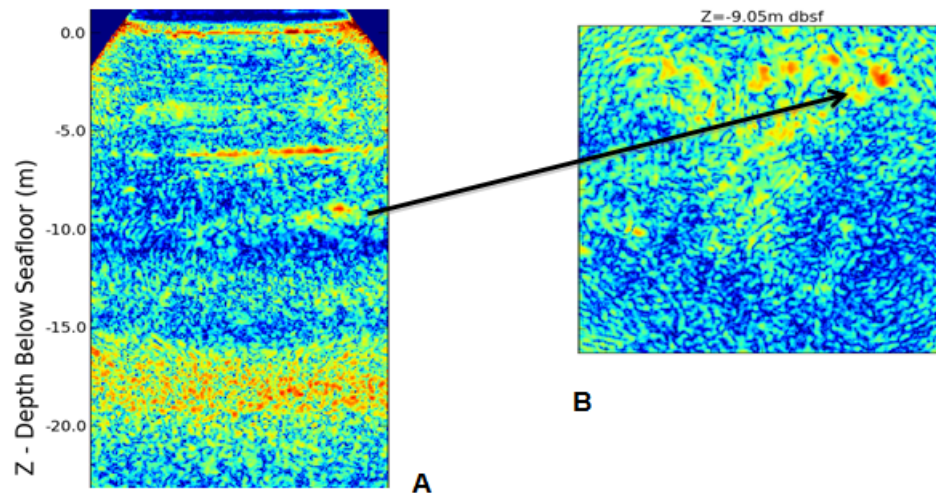


Figure 58: Illustration exhibiting in A a vertical elevation view (10m lateral extent) where a distinct anomaly suggestive of a boulder is noted. Data panel B is the corresponding horizontal data slice (at 10 m depth). Source: PanGeo Subsea Inc. AC data archive, 2011.

Figure 59 exhibits a near surface horizontal data slice which highlights boulder/cobble clusters and isolated anomalies with an associated comparison boulder found proud at the surface.

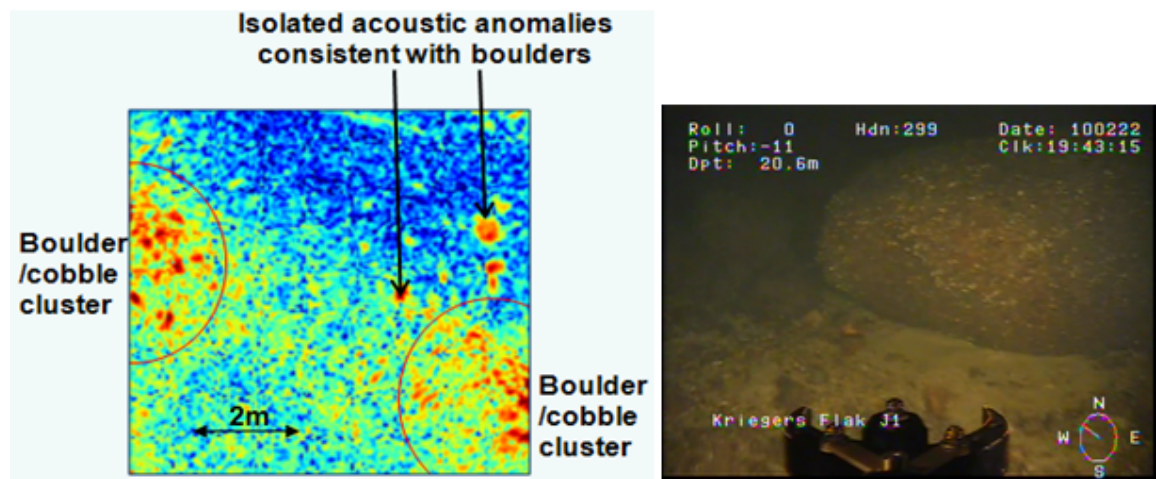


Figure 59: Example of a horizontal section which displays isolated boulder type anomalies, and boulder/ cobble cluster signatures as imaged near the surface, with a typical boulder found proud at the site. Source: PanGeo Subsea Inc. AC data archive – Kriegers Flak, Baltic Sea, 2010.

The cross-section in Figure 60 shows a 3m thick gravel/cobble layer buried at a depth of 11.0m sandwiched between clay soil and sandy soil, which are relatively acoustically transparent. The gravel is acoustically reverberant so has a pixelated texture as shown in the cross-section view of this gravel/cobble layer. Typically, gravels appear as patches, layers, and discontinuous rough patterned slices. Gravel/cobble layers appear as regions of high background acoustic intensity with localized areas of extremely high acoustic

intensity, which indicate cobble sized particles, higher concentrations of gravel, or small boulders, as illustrated in the sequence of horizontal sliced images in Figure 61.

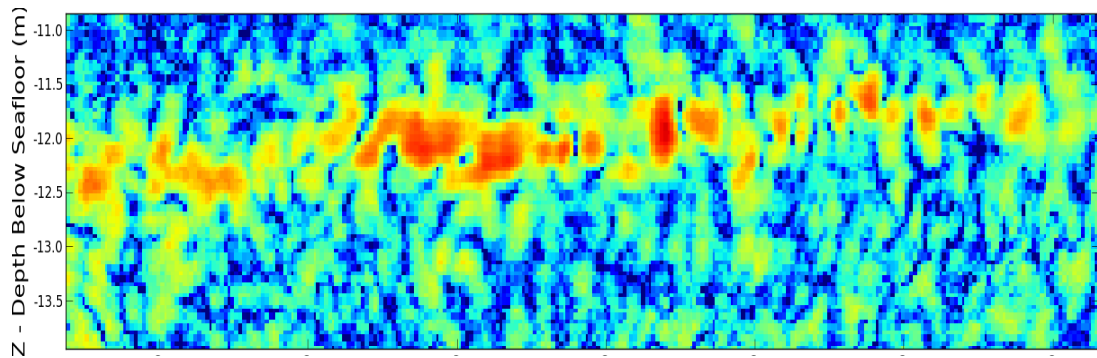


Figure 60: Example of a vertical cross-section (3m thick x 12m length) gravel / cobble layer buried at a depth of 11.0m, sandwiched between clay soil and sandy soil. Source: PanGeo Subsea Inc. AC data archive, 2011.

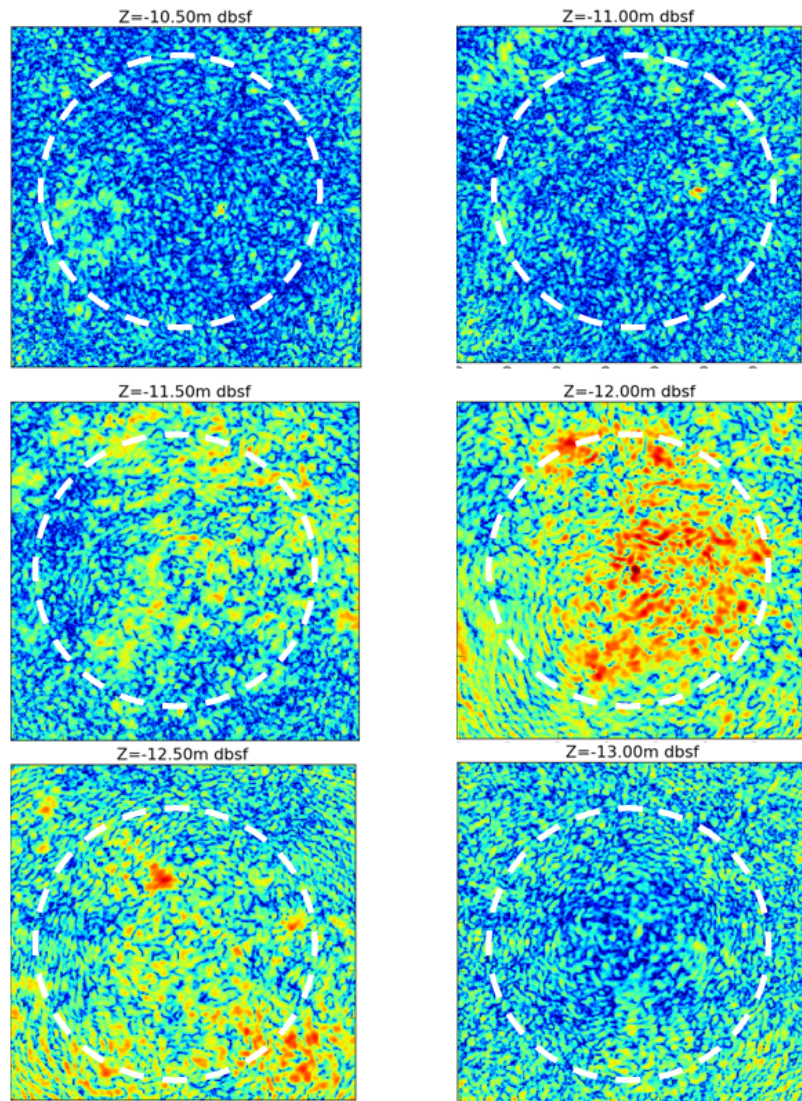


Figure 61: Example horizontal slices through the acoustic core (12 m x 12m) presenting examples of cobble sized particles, higher concentrations of gravel, and small boulders. Source: PanGeo Subsea Inc. AC data archive, 2011.

As a further example of the presence of boulder clusters, data was acquired in the Baltic Sea, in a region of highly complex geology. A feature of the site was the recurrence of boulder clusters and layers. In one Acoustic Core site a feature was noted in both the parametric and high frequency chirp data, which were interpreted as a mound of boulders and cobbles typical of a glacial moraine deposit. Individual boulders merged to form the curved band as noted in Figure 62.

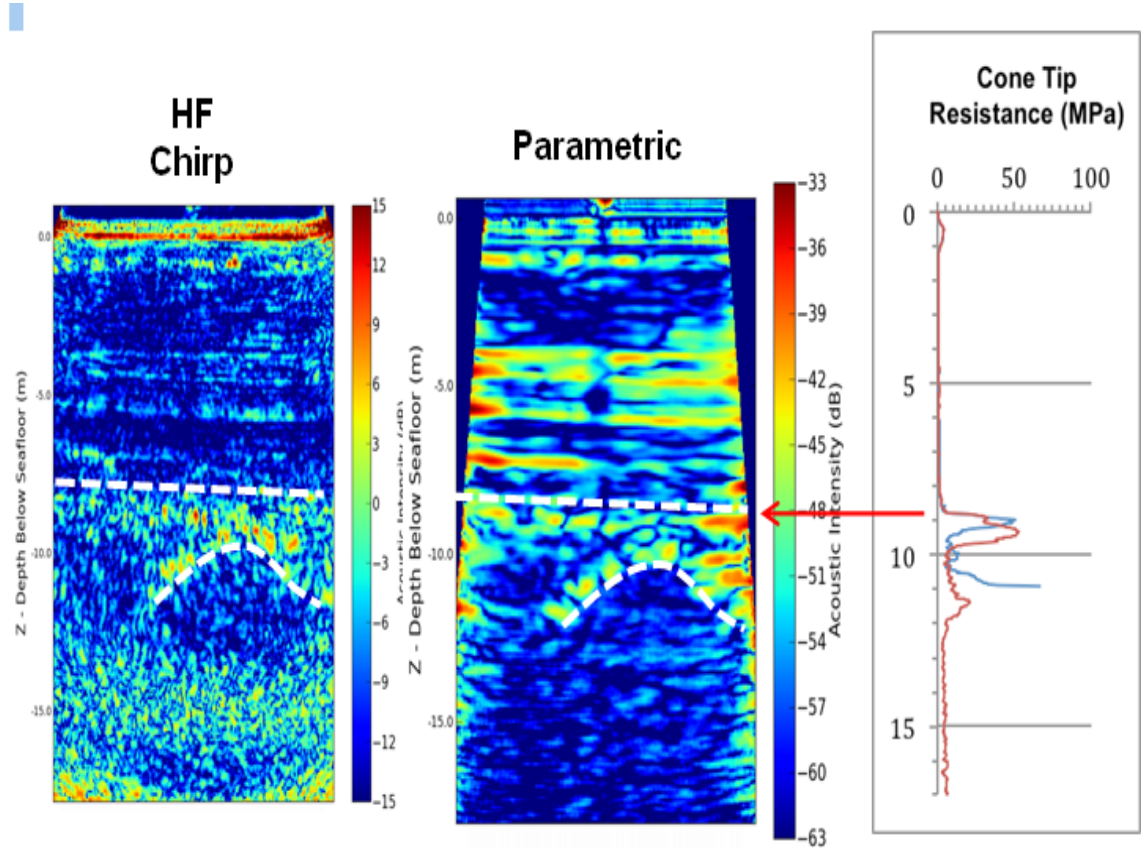


Figure 62: Example of two vertical slices (approximately 10 m widths, 15m depths) through rendered Acoustic Core SAS data for both the High Frequency Chirp and for the Parametric data. The CPT data shows spikes correlating to the boundaries. Source: PanGeo Subsea Inc. AC data archive, Baltic Sea site, 2011.

Figure 63 illustrates associated High Frequency Chirp cross-sections through the moraine with plan view slices descending through the moraine from 9.00m to 10.50 m depth

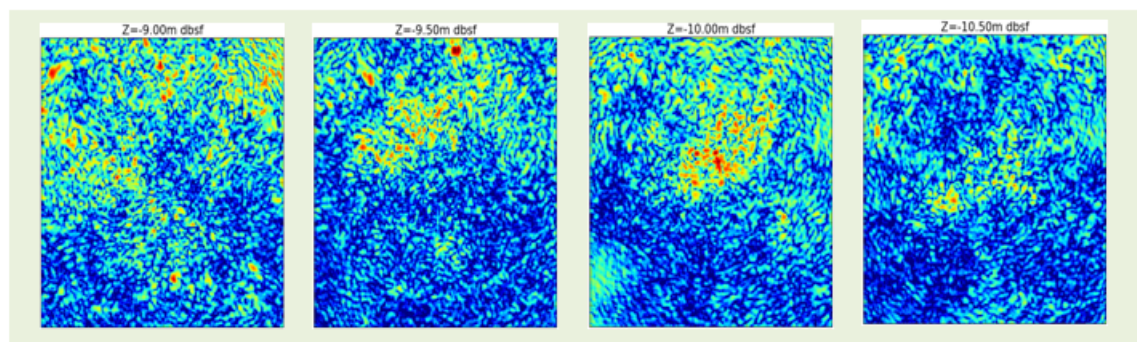


Figure 63: High Frequency Chirp slices through the moraine. Source: PanGeo Subsea Inc. AC data archive, Baltic Sea site, 2011

4.4 Acoustic Texture Imaging And Interpretation

The stability and stationary operation of the ASI permits the analysis of acoustic texture as a means of differentiating various types of seabed soils. Acoustic texture is interpreted in conjunction with acquired borehole or CPT data.

The most easily recognized marine deposits are those containing gravels and cobbles, since they produce a highly reverberant acoustic return. A cobble layer located close to the surface of the seafloor acts as an extremely strong reflector. Depending on the acoustic impedance contrast with the surrounding soil matrix, boulders can act as extremely strong reflectors. The resulting size, shape, and acoustic intensities of these types of anomalies are used to determine whether the boulder is isolated or is one of a cluster of boulders as shown in Figure 64 which presents three spatial cross-sectional slices. Slicing through the data cube in plan view permits the individual cobbles to be isolated for further conformation.

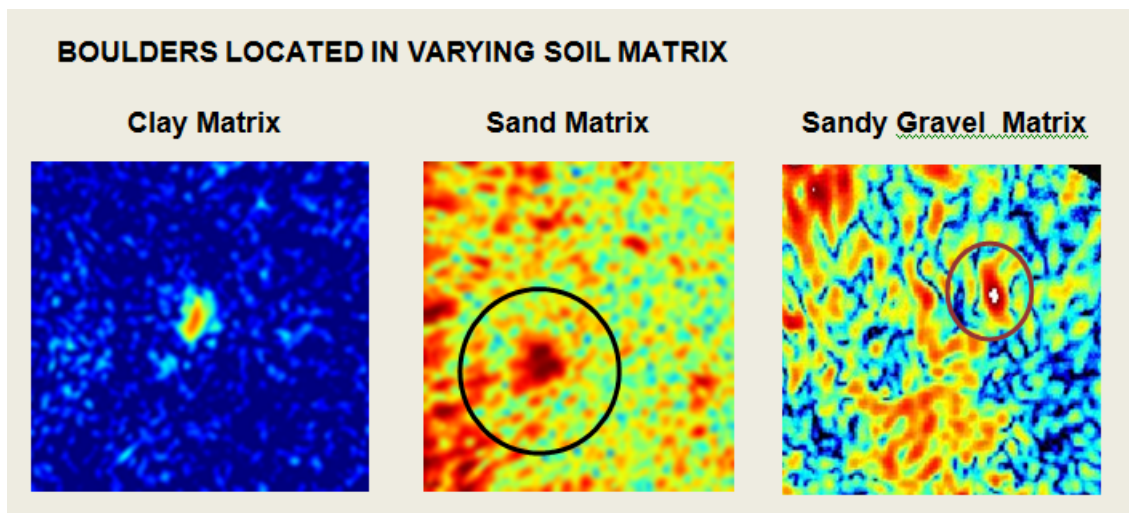


Figure 64: Three High Frequency Chirp horizontal examples of boulders as detected in a clay sediment, in a sand matrix and in a sandy gravel layer. Source: PanGeo Subsea Inc. AC data archive, Norwegian fjord, 2011.

PanGeo Subsea's Acoustic Corer™ was used in 2009 to conduct a demonstration survey at the StatoilHydro Ormen Lange site in the Norwegian Sea in approximately 410m water depth. An erosion boundary was imaged at the base of a till layer as illustrated in Figure 65.

The boundary, indicated by the dashed red line, is an irregular surface ranging in depth between 11m and 13m. The erosion boundary divides the till layer from an underlying clay soil, which has a different acoustic texture to that of the till. The till is thought to contain considerable amounts of cobbles and gravel owing to the reverberant nature of its acoustic return.

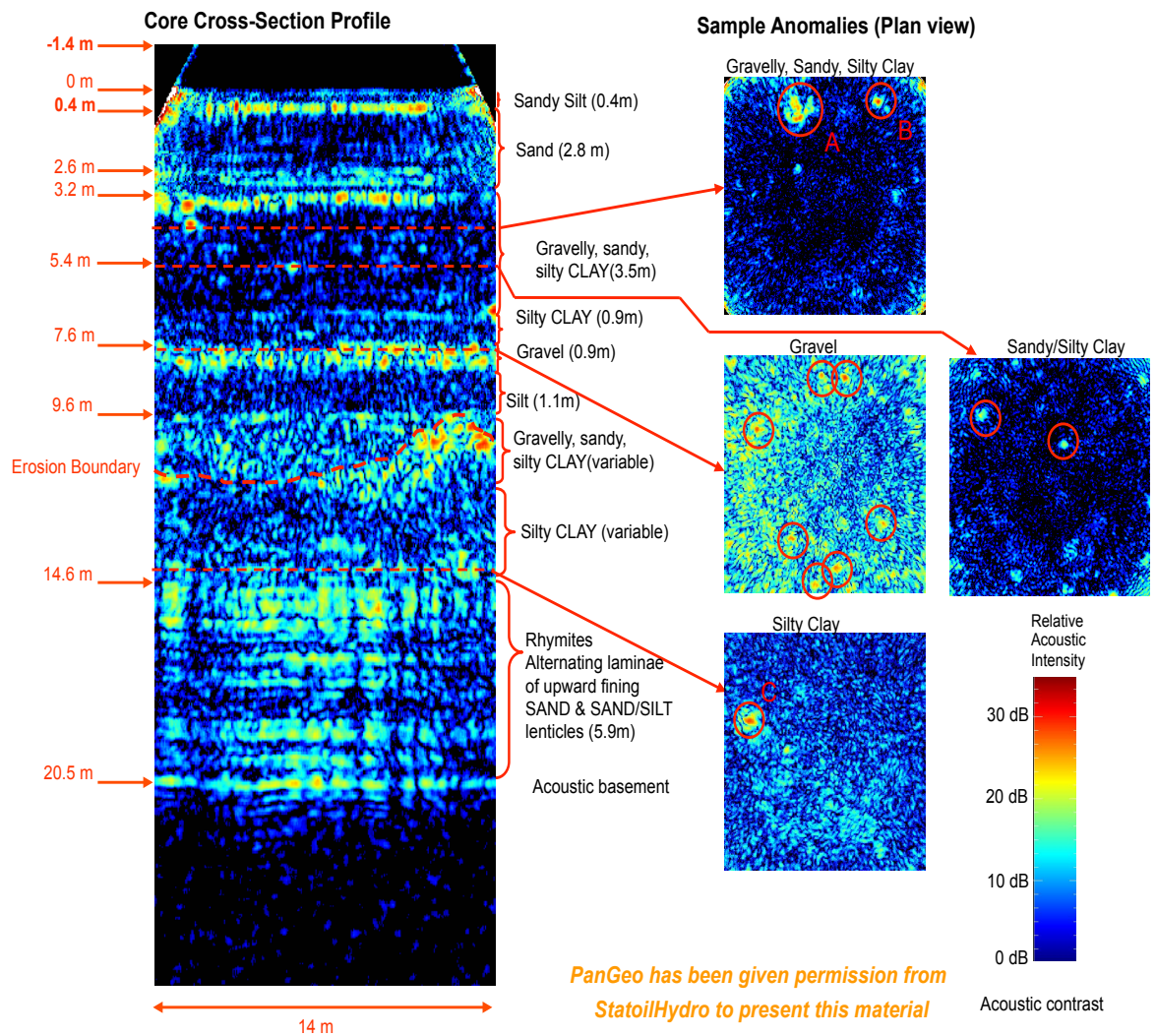


Figure 65: Acoustic core vertical slice example after the SAS rendering with accompanying horizontal slices. Source: StatoilHydro Ormen Lange Acoustic Corer trials in the Norwegian Sea; PanGeo Subsea Inc. marketing archive 2009, released by permission.

The erosion boundary is geotechnically significant, given it is associated with the highest magnitudes of unit weight and undrained shear strengths as recorded by cone penetrometer tests. The high shear strengths are attributed to the increased coarse grain content.

After acquiring and rendering the SAS data into an Acoustic Core result, it was noted that the erosion boundary could very weakly and ambiguously be observed in previously acquired sub-bottom profiler records. However, the subtle undulations in the boundary, as observed in the extracted vertical slice out of the Acoustic Core data, had been lost in the sub-bottom profile owing to its scale, lack of spatial resolution and general smearing of stratigraphic detail, which is a characteristic of towed body profilers.

Figure 66 illustrates the comparison of the Acoustic Core data set with the borehole data with the interpretation made for the Acoustic Core.

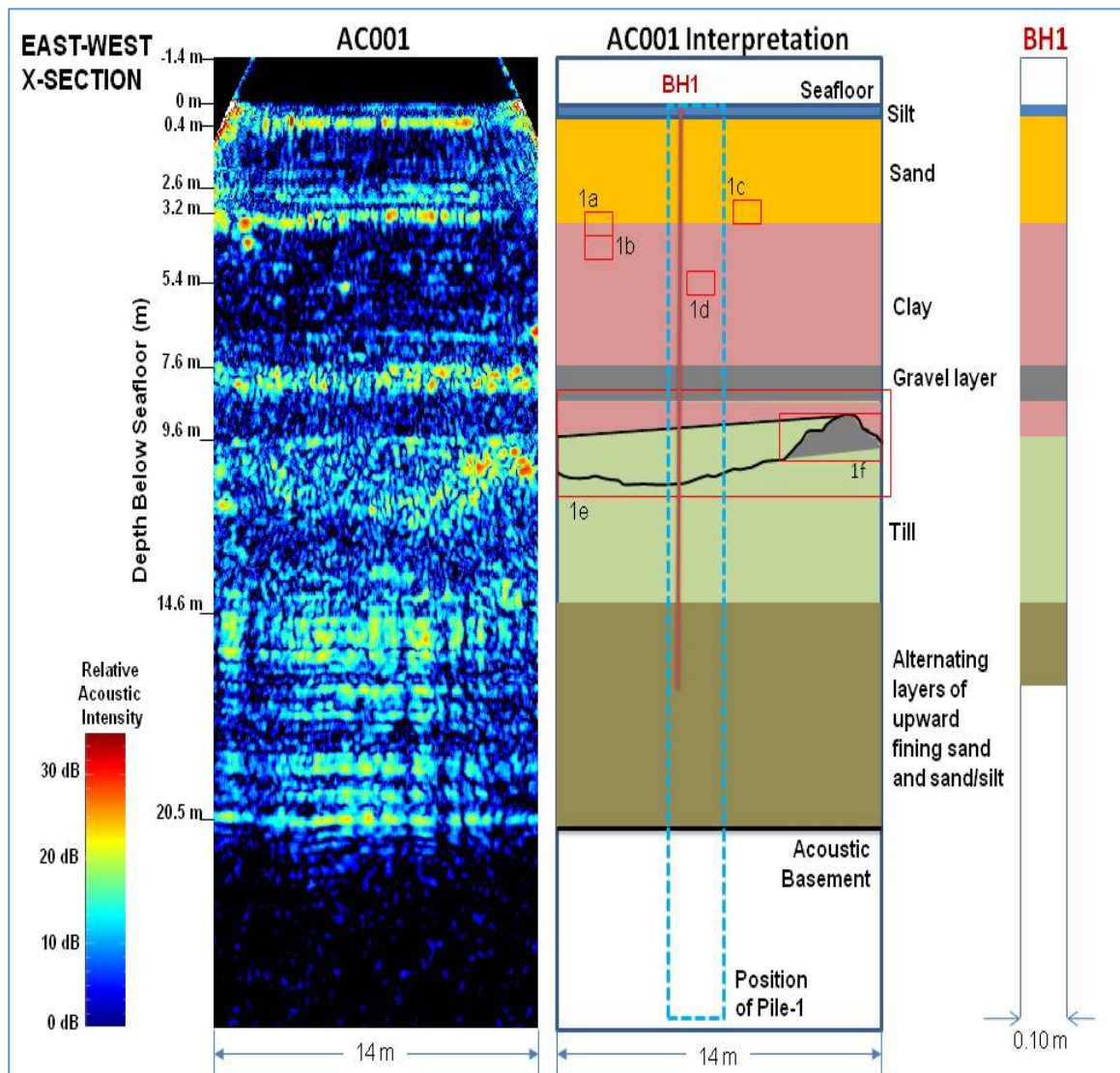


Figure 66: Acoustic core vertical slice example after the SAS rendering with accompanying interpretation and comparison to the geology of the borehole. Source: StatoilHydro Ormen Lange Acoustic Corer trials in the Norwegian Sea; PanGeo Subsea Inc. marketing archive 2009, released by permission.

4.5 Imaging Seafloor Features

It is very common to image features associated with previous site investigations. One site contained shallow features that were interpreted as debris and a CPT rod (see Figure 67).

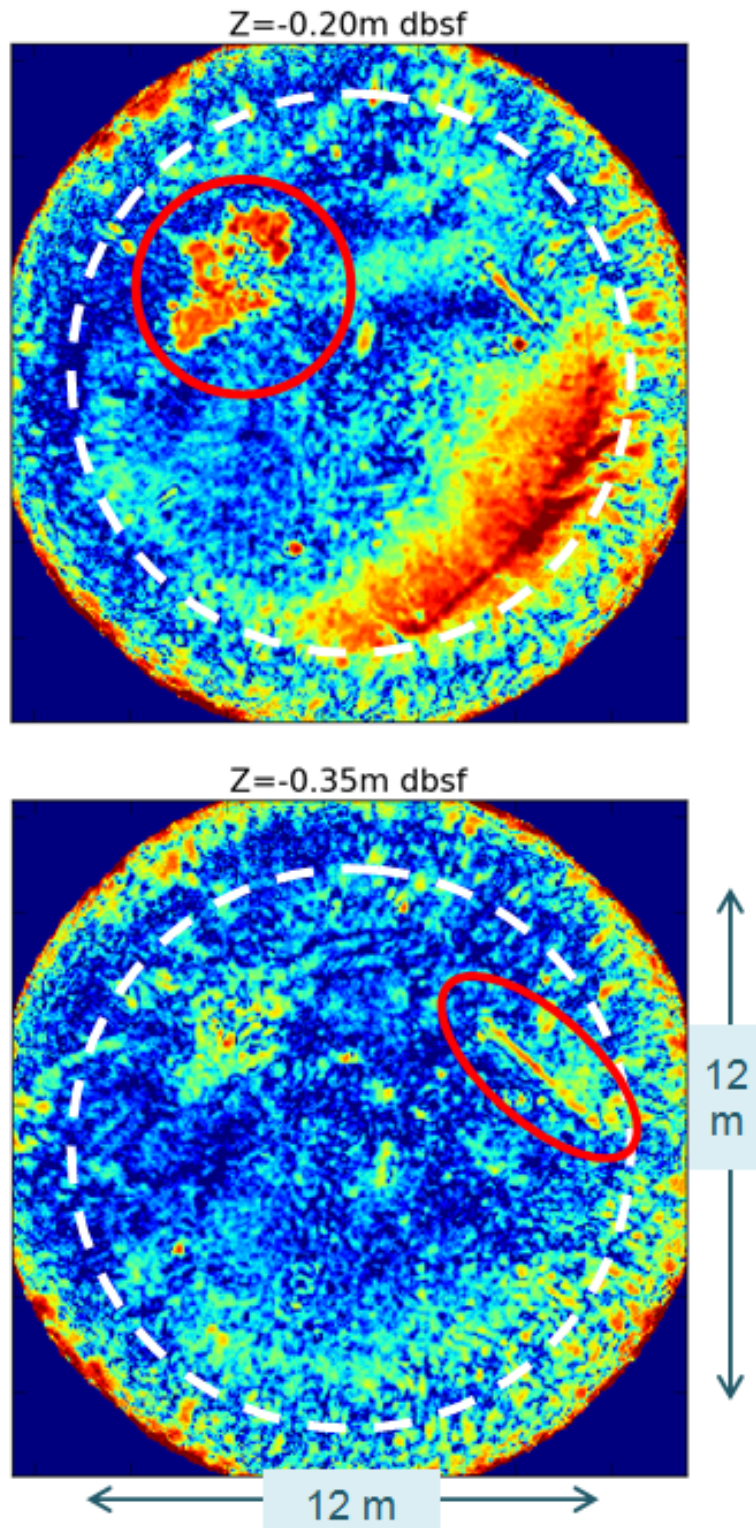


Figure 67: Acoustic core horizontal SAS High Frequency slices; the upper slice of debris (in red circle) and the lower slice revealing CPT rod lying on the seabed (in red circle). Source: PanGeo Subsea Inc. marketing archive, Baltic Sea site, 2010.

The two images shown in Figure 68 were acquired in the Baltic Sea at a site of previous geotechnical testing. This depression in the seafloor is 2m in diameter and 0.3 to 0.5m deep. The depression was caused by a cone penetrometer that was retracted due to the danger of a punch-through of what was believed to be possible gas beneath the seabed. The depression is shown in plan view and section. A further investigation of the feature

revealed the aborted CPT investigation to be unnecessary. The ASI Acoustic Core results at the site quickly provided the information that could not be gathered physically, and the data collected revealed that the sub-seabed was relatively homogeneous free of geo-hazards. Figure 69 presents two vertical cross-sections.

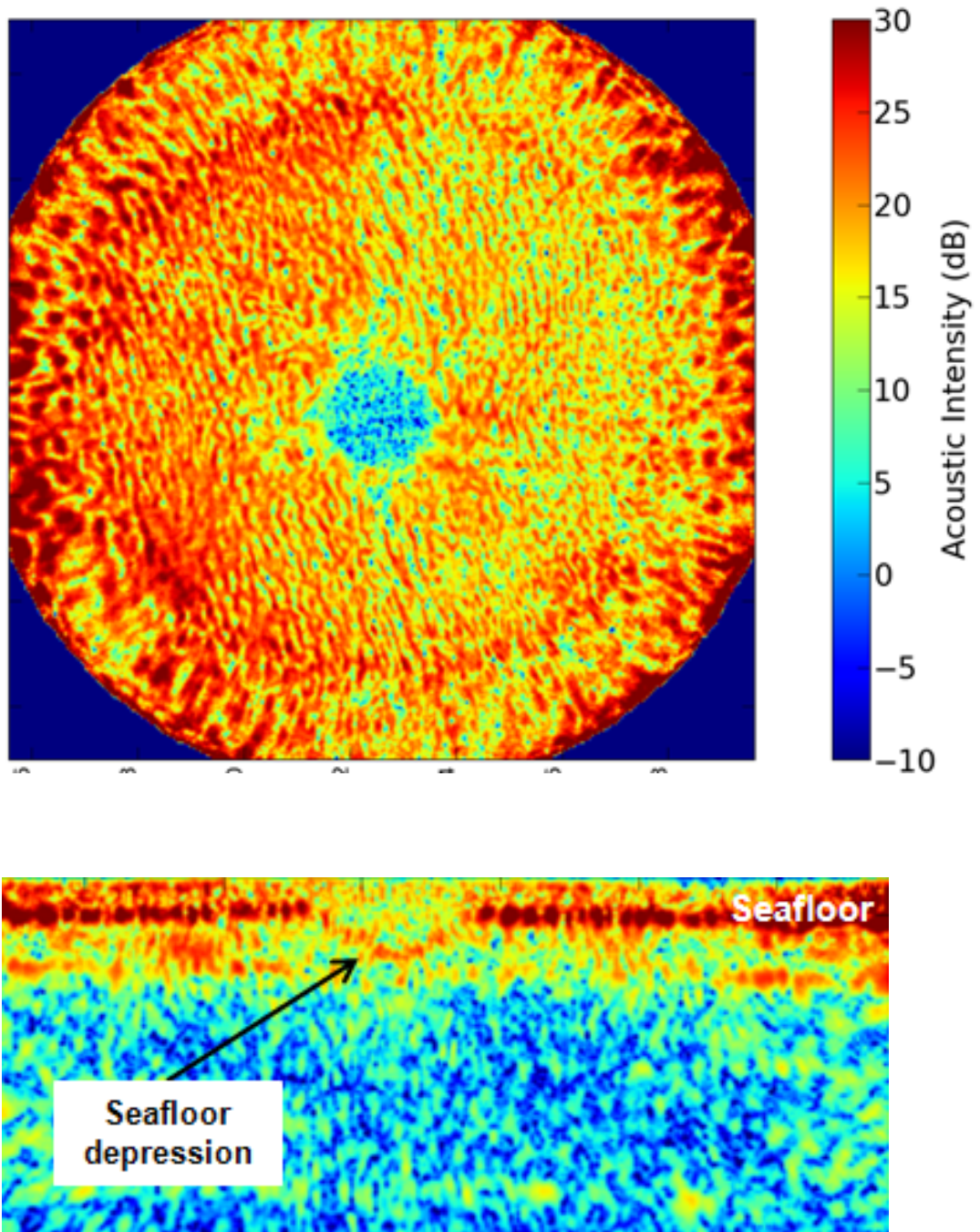


Figure 68: Top image is a horizontal SAS High Frequency image at the seabed (12m diameter) with a clearly pronounced indentation noted near the center of the image. The lower slice presents the seabed depression in the elevation view (depression is approximately 2m wide with a depth of 1m). Source: PanGeo Subsea Inc. marketing archive, Baltic Sea site, 2010.

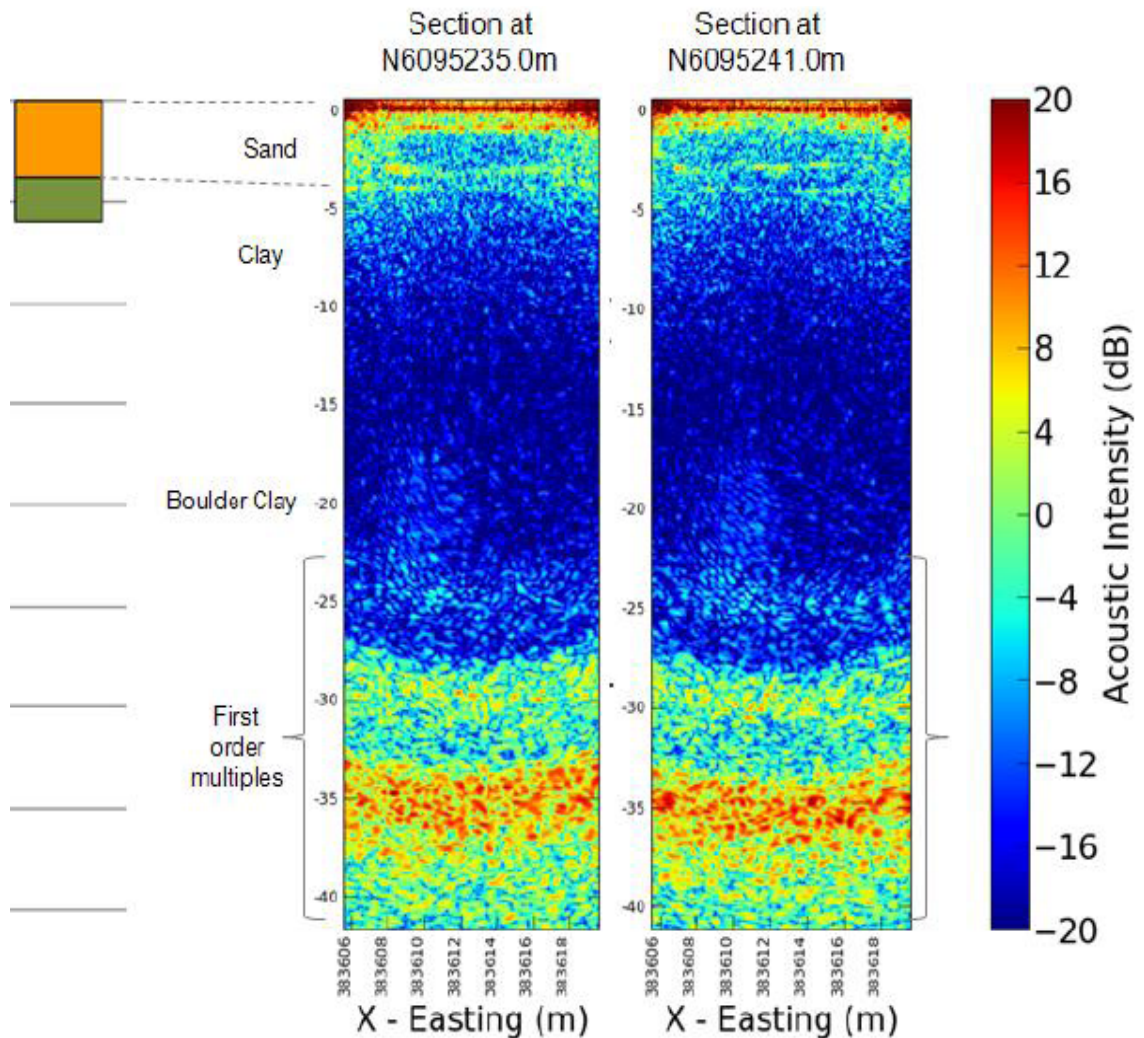


Figure 69: Two vertical SAS High Frequency profiles extending from where the CPT investigation aborted. The resulting Acoustic Core verified that no buried acoustic anomalies were present at the site. Source: PanGeo Subsea Inc. marketing archive, Baltic Sea site, 2010.

Further Baltic Sea seafloor features displaying imprints of previous site investigations are highlighted and annotated in Figure 70. Cross-sections through these imprints show regions of higher acoustic intensity returns caused by the densification of the sediments directly below the imprint. Buried spud can imprints from jack-up rigs could be identified in a similar way.

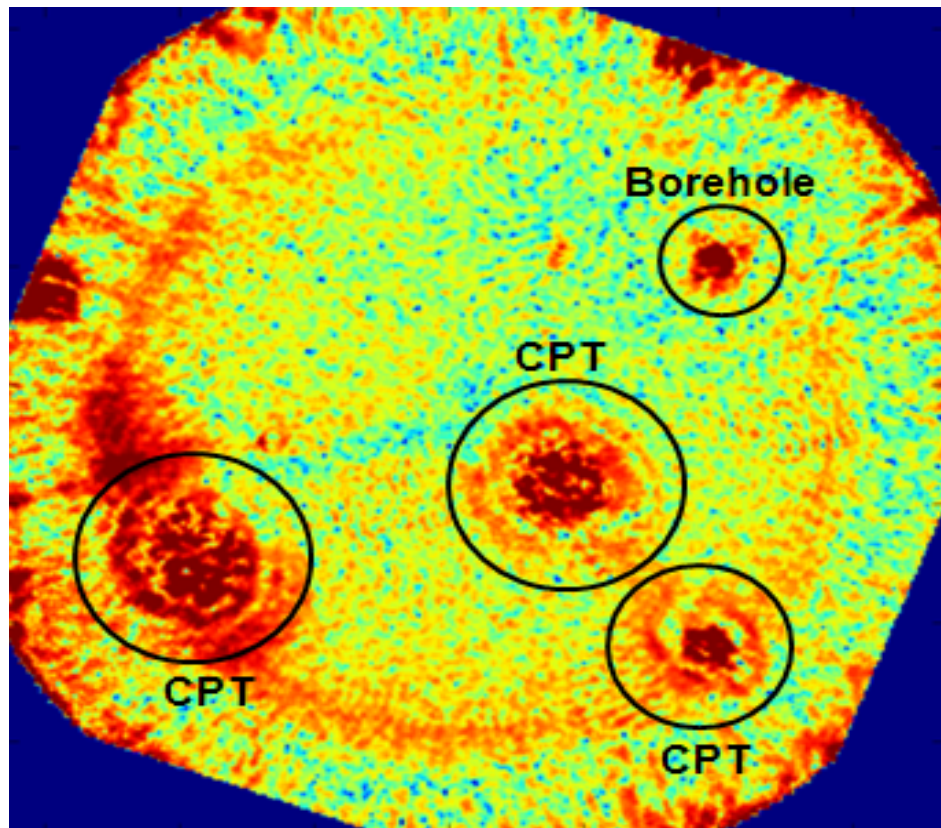


Figure 70: Annotated features in a horizontal SAS High Frequency at the seabed (12m diameter). Source: PanGeo Subsea Inc. marketing archive, Baltic Sea site, 2010.

4.6 Interpreting And Comparing Rendered Acoustic Data With Geotechnical Data

In 2011, Dong Energy approached PanGeo Subsea to acquire 25 acoustic cores to redefine the distribution and character of their region's sedimentary character. The application of the ASI to construct detailed imagery of the Anholt site's sub-seabed character was exactly what was envisioned in the original PhD thesis at Bath by Guigné in 1986 and supports the arguments presented in the journal publication by Clark and Guigné in 1988.

The Anholt investigation is an illustrative case of the value proposition whereby the ASI approach of assessing and analyzing a wide area detailed acoustic core answer product can bridge the geo gap. This was deemed essential to Dong Energy. Through the use of PanGeo's Acoustic Corer, the rendered interpreted data provided greater spatial information about buried geo-hazards—including the extent and size distribution of geo-hazards such as buried boulders, cobble clusters, and gassy sediments—for their region. This redefined the surficial sediment character and distribution for the Anholt site, thereby greatly mitigating engineering risks associated with pile installation in the region⁸. The Anholt wind farm is located in a region of extremely varying geology. Overall, the complexity of the site is such that it was found to be impossible to reliably interpolate and predict anomaly concentrations at the planned turbine foundation sites based only on the comprehensive geotechnical site investigations conducted and from accompanying sub-bottom acoustic profiling.

⁸ The PanGeo Subsea Inc. geoscience team assembled to process the acoustic core data, to analyze the findings and to fuse the various geotechnical datasets with the acoustics into final interpretations was led by I. McDermott and A. Brown with underpinning geophysical support by J.Y. Guigné, A. Gogacz R. Laidley, C. Clements, and B. Hunt. The program management was provided by G.Dinn. Final certifying of the geoscience results was by J.Y. Guigné.

The ASI answer product not only verified the validity of CPT soil profile results, but added value by showing the lateral extent, depth variability, and complexity of the soil horizons. Overall, correlation between the acoustic core data collected and the CPT results were excellent. The acoustic core stratigraphy results explained the observed variation in repeated CPT results. It also explained the reason (i.e., boulder/cobble clusters and layers) why CPT's terminated earlier than their target.

In acoustic core data, areas of high cone resistance correspond to strong reflections in the acoustic profile. Figure 71 highlights two examples taken at the Dong Anholt wind farm site.

In most cases the acoustic core answer product provided important spatial context but also delivered a means to validate the reliability of the cone penetrometer based data. Good correlations occurred in simple uniform or homogeneous geostatistics; however, in more complex sites, discrepancies occurred, primarily reflecting the lack of spatial coverage by the CPTs and, because of the non-linear soil interactions or influences commonly present in mixed complex seabeds, that limits the reliability of geotechnical investigations in such sites.

Figure 72 displays a discrepancy at event A, where the acoustic core shows the interface to be 1.25m shallower than in the CPT data. This is due to the placement of the CPT; it sampled a small atypical area of stratigraphy and did not accurately represent the local trend. Figure 73 is a comparison that displays the type of laterally varying stratigraphy that cannot be spatially mapped by a conventional CPT or borehole site investigation survey.

Of importance to many wind farm seabed sites is the accurate detection and mapping of "gassy sediments" (e.g. Orange et al., 2005; Duck and Herbert, 2006). This is extremely difficult to do as the gas in the sediment acts as a strong reflective mirror due to impedance mismatches between the gas and sediment, thus its presence creates a masking of the general surrounding sediment character by imposing an acoustic blanking footprint.

The ASI's use of SAS multi-aspect views allows for coherent sediment returns to be detectable in the presence of gas. Depending on the quantity of gas, stratigraphy and anomalies may still be detected below gas layers owing to this multi-aspect set of views.

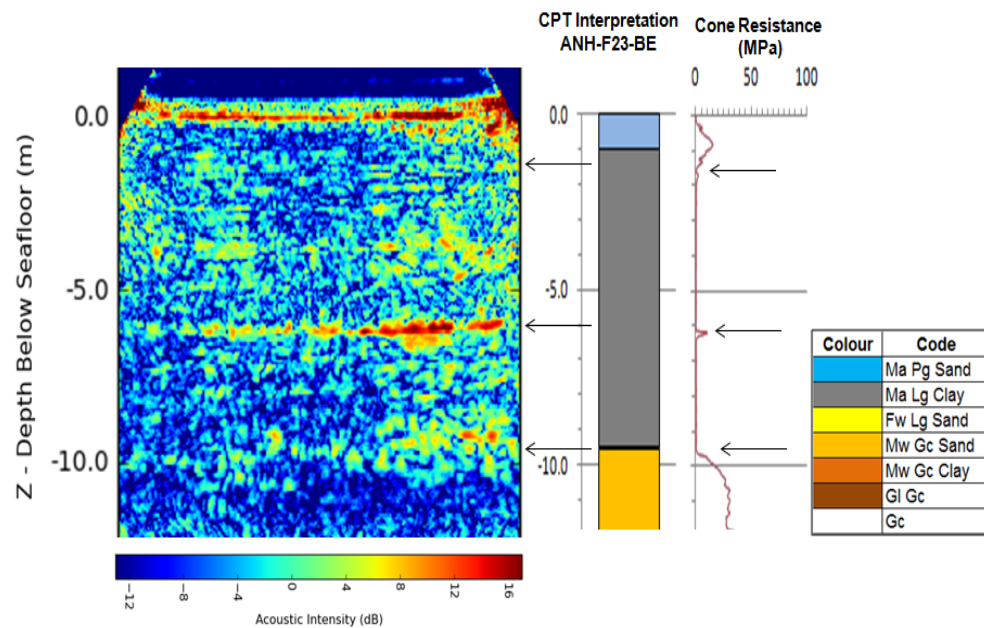
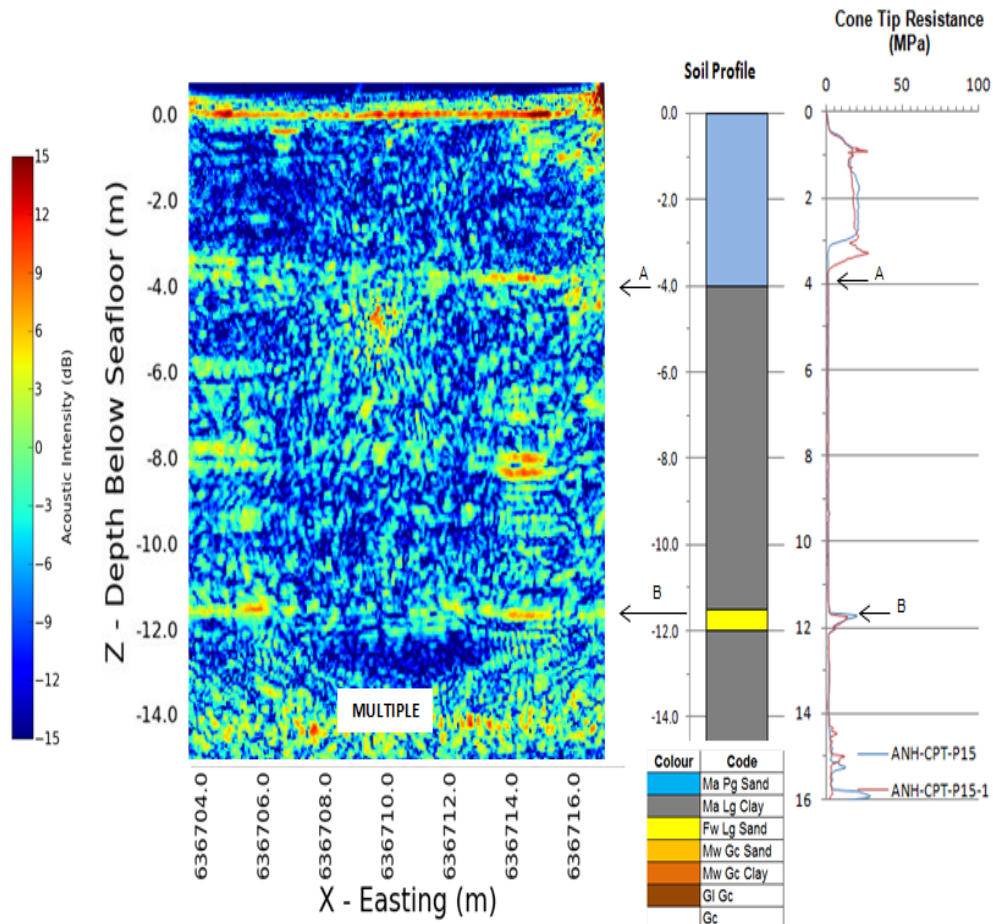


Figure 71: Vertical profile slices taken at two separate sites and compared to geotechnical information. Both sites display good agreement between the CPT data and the acoustic cores, with the acoustic data displaying more events than are visible in the CPT data. Source: PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011.

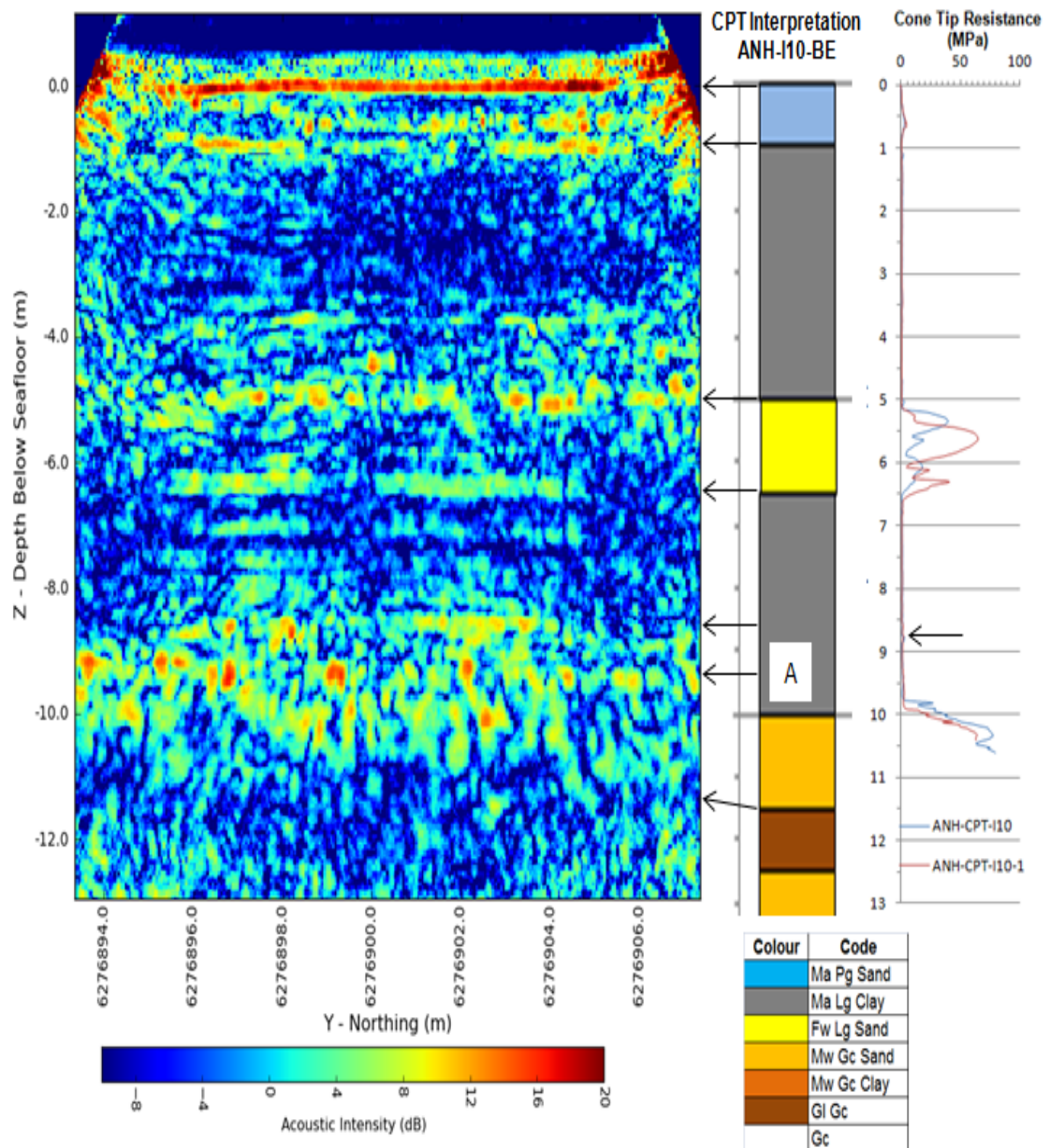


Figure 72: Vertical profile slice comparing to geotechnical CPT information. A major discrepancy exists at event A. Source: PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011.

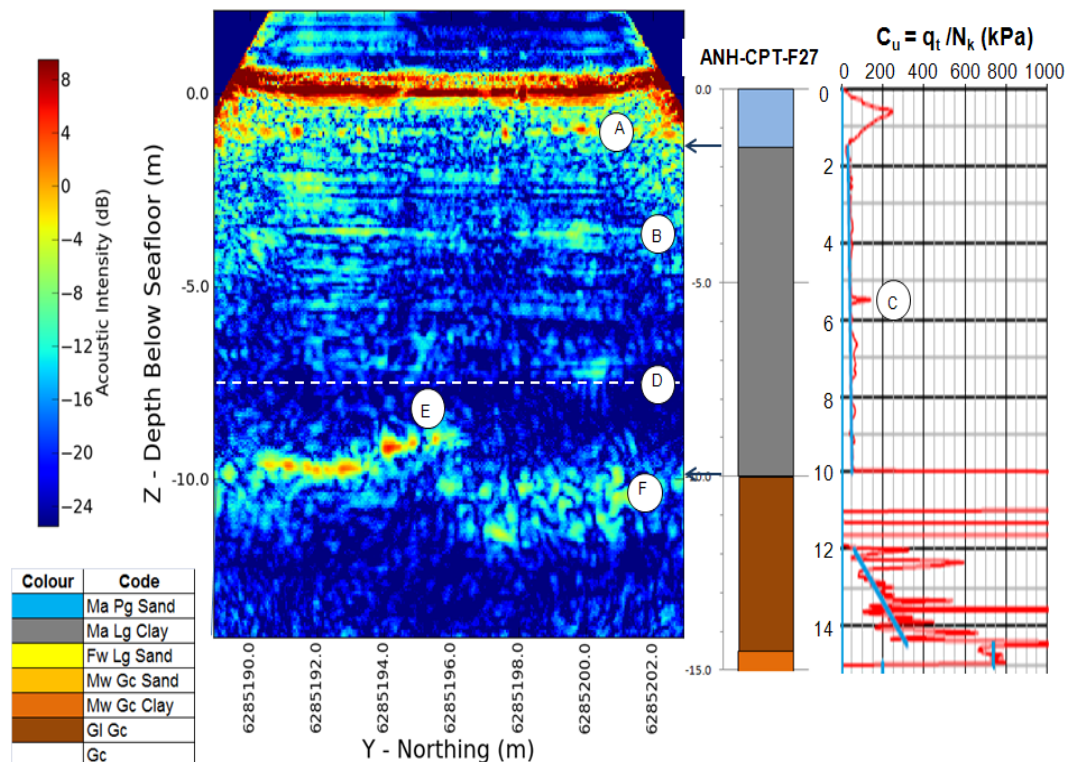


Figure 73: Vertical profile slice comparing the acoustic interpretation, borehole and geotechnical information, displaying with inserted letters the different types of laterally varying stratigraphy that cannot be spatially mapped by the CPT or borehole data alone. Source: PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011.

Both the High Frequency chirp and the Parametric sonar detected the spatial distribution and thickness of the gas in the Anholt Baltic Sea site. In contrast, gas blanks strata in conventional seismics. It was noted that sub-bottom profiling could not define the extent of the gas in the sediment and the data did not tie in well with CPT measurements. Figure 74 presents a typical continuous shallow seismic section over this gas region with CPT results.

Figures 75 and 76 illustrate an example of the ASI's interrogation of the gas and demonstrates the clarity of its distribution in the sub-seabed. This was observed in the vicinity of the Anholt wind farm. The gas was located at 6.2m depth below the seafloor in a marine late glacial clay unit.

North

South

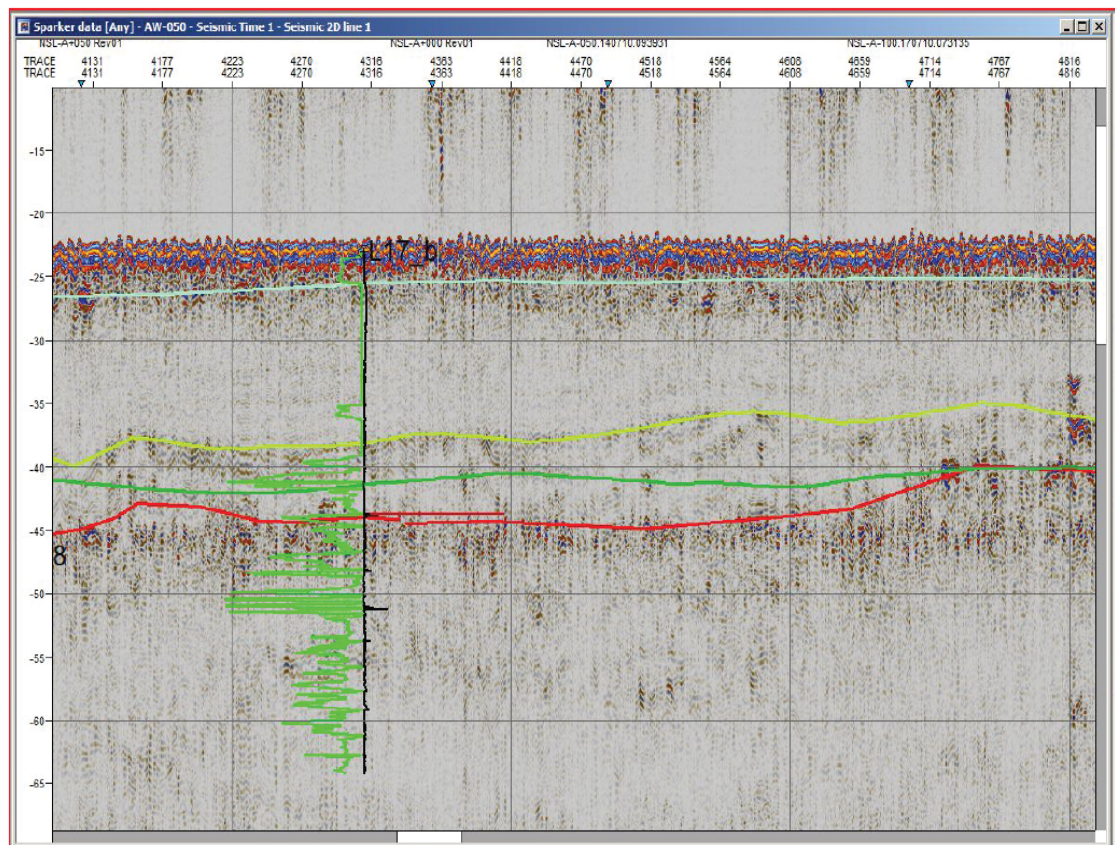


Figure 74: Typical conventional sub-bottom profile with associated CPT response; noticed the smeared masking character in the record caused by the presence of gas in the sediment. Source: PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011

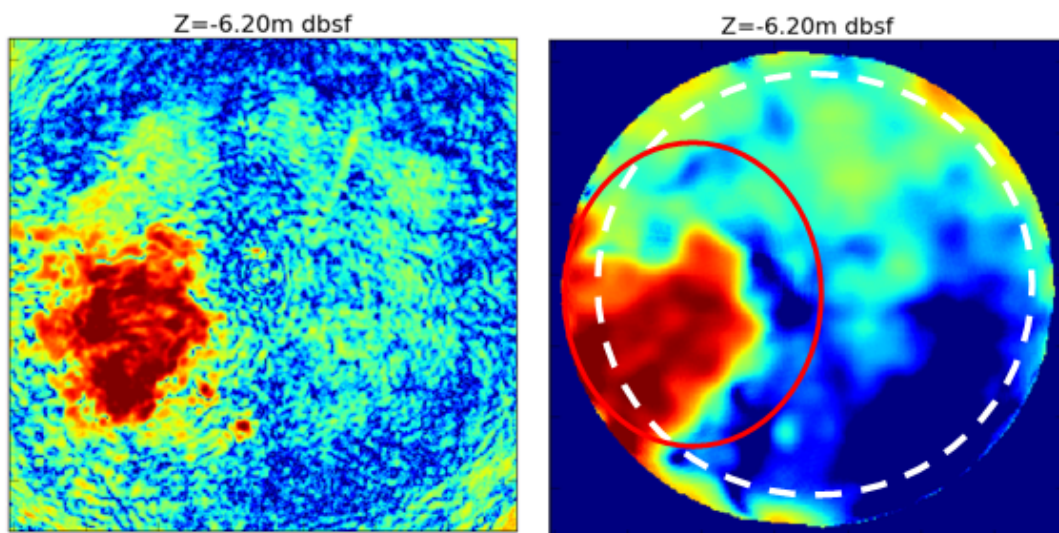


Figure 75: Two associated horizontal slices for the SAS rendered High Frequency Chirp and for the Parametric Data, highlighting the spread of the gas layer. Source: PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011.

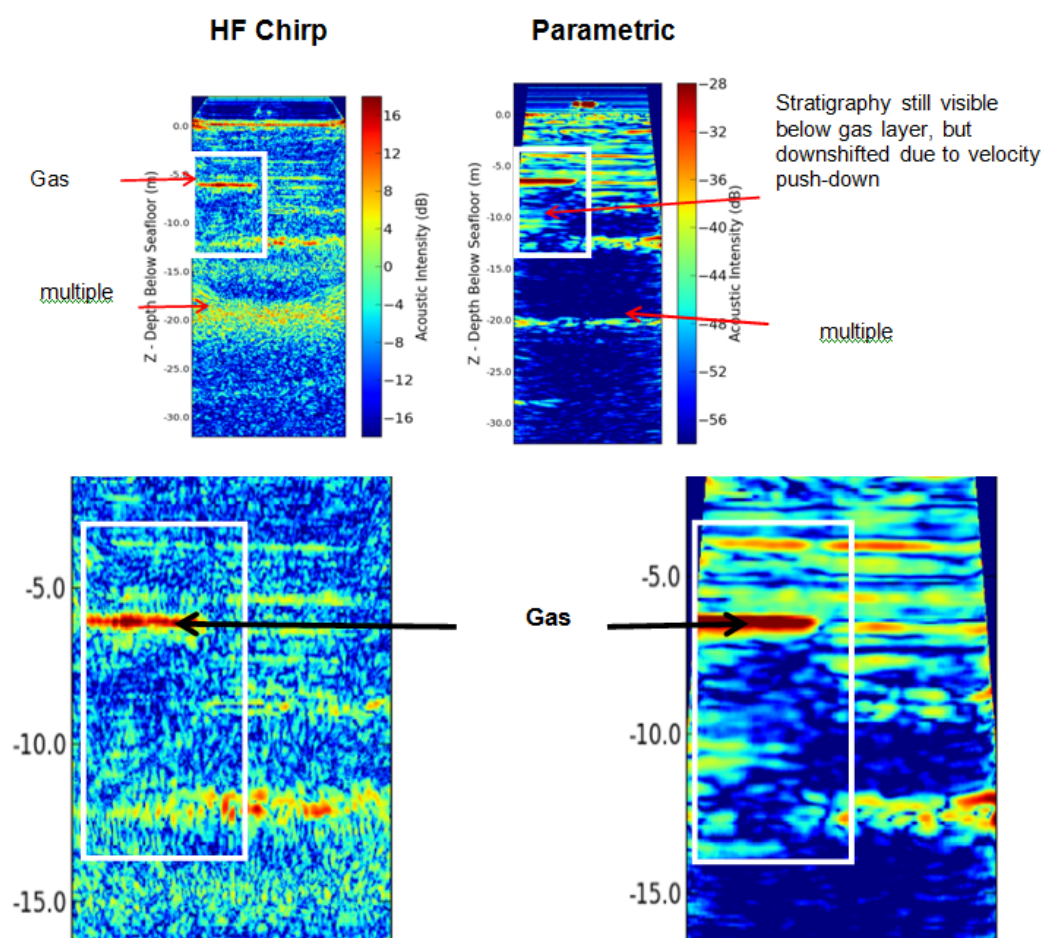


Figure 76: Two vertical SAS profiles for the High Frequency Chirp and for the Parametric Data, highlighting a gas layer. Source: PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011.

As previously mentioned the Anholt wind farm is located in a region of extremely complex geology. The overall complexity of the site is such that it is impossible to interpolate and predict anomaly concentrations at turbine foundation sites based on the geotechnical data alone. By acoustically interrogating the seabed in a stationary manner and delivering an acoustic core answer product, greater spatial information about buried geo-hazards, including the extent and size distribution of buried boulders, gas layers, and cobble clusters, were quantifiably reached with confidence and reliability.

The Acoustic Corer survey of the Anholt wind farm successfully provided the results Dong Energy needed to reduce their pile installation risk. From the interpretations and distributions of the anomalies, a statistical assessment was made of the distribution of the anomalies where they were found in the sub-seabed.

Through the analysis of the 25 cores with their characteristics, 58% of the anomalies were located in the Marine Late Glacial Clay, which overlies the Melt Water Glacial Units, whilst 96% of anomalies were located in the uppermost 15m of soil column.

Figure 77 graphically presents a descriptive overview of the distribution. Figure 78 highlights the distribution by diameter whilst Figure 79 presents the distribution by depth leading finally to a total number of anomalies by geological units (see Figure 80).

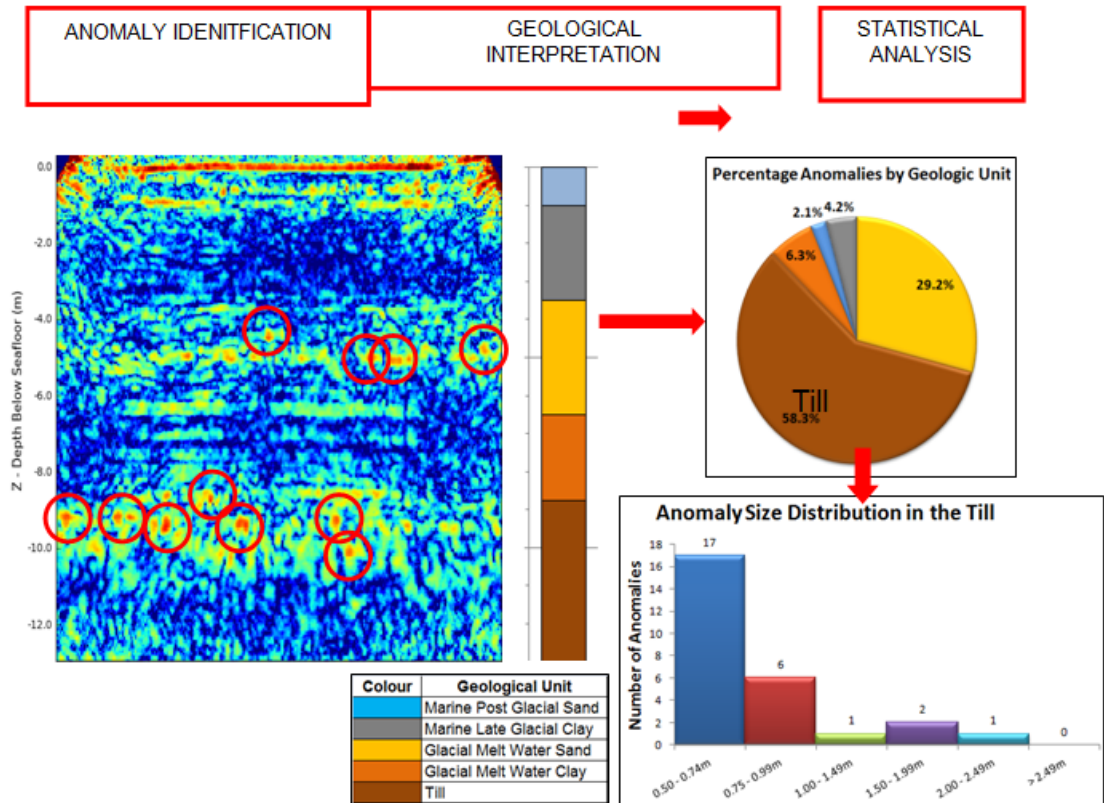


Figure 77: Descriptive Analysis. Source: Based on the data exhibited in the Anholt study, PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011.

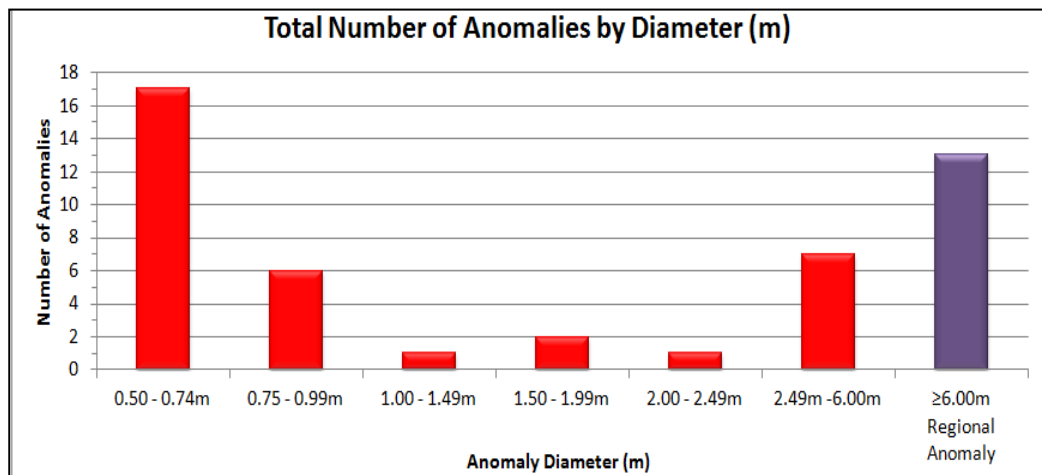


Figure 78: Total Number Of Anomalies by diameter. Source: Based on the data exhibited in the Anholt study. Source: Based on the data exhibited in the Anholt study, PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011.

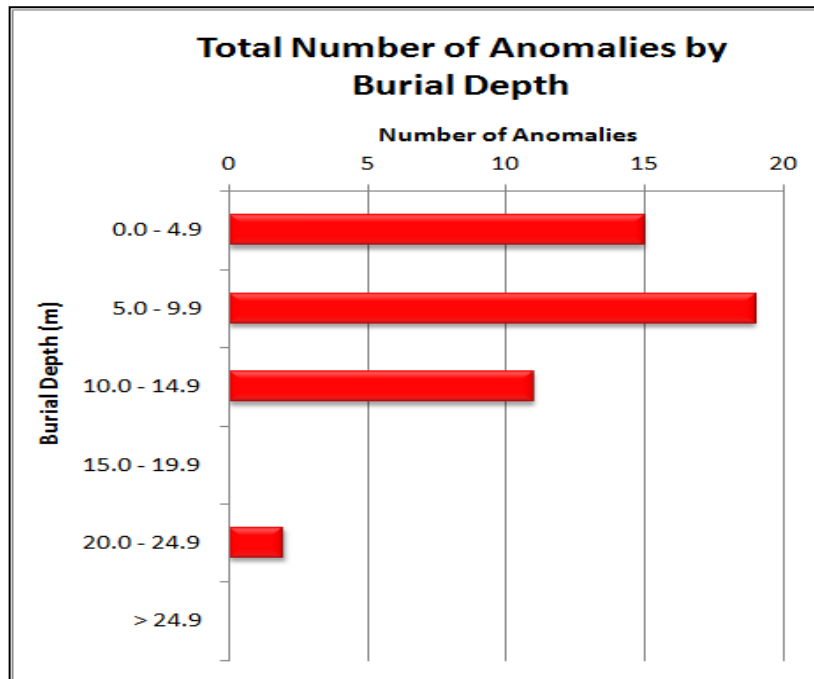


Figure 79: Total Number Of Anomalies by Burial Depth. Source: Based on the data exhibited in the Anholt study, PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011

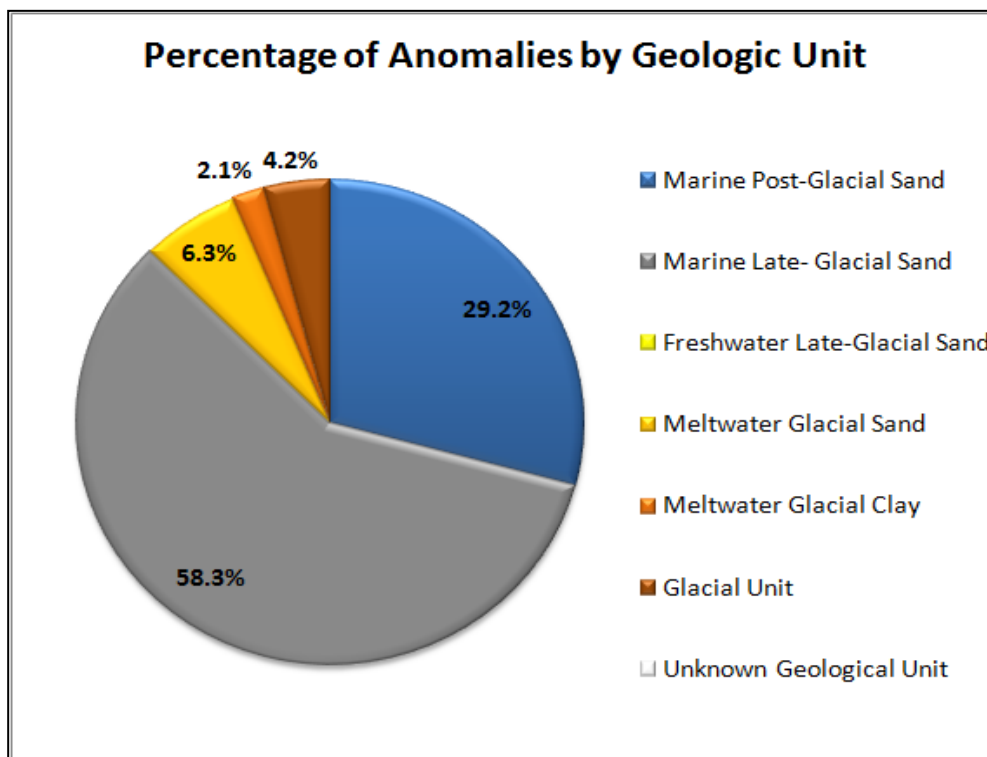


Figure 80: Total Number Of Anomalies by geological units. Source: Based on the data exhibited in the Anholt study, PanGeo Subsea Inc. RPT-03131-1 AC Dong Anholt Final Report Dec 2011.

References Cited

Duck, R.W. & Herbert, R.A. (2006). High-resolution shallow seismic identification of gas escape features in the sediments of Loch Tay, Scotland: tectonic and microbiological associations. *Sedimentology* (53), 481–493.

Guigné J. Y. (1986). *The concept, design and experimental evaluation of 'acoustic sub-seabed interrogation.'* Ph.D. thesis, University of Bath, Bath, England.

Clark, J.I. and Guigné, J.Y., (1988). Marine Geotechnical Engineering in Canada. *Canadian Geotechnical Journal*. (25)2, pp.179-198.

Orange, D.L., Garcia-Garcia, A., McConnell, D., Lorenson, T., Fortier, G., Trincardi, F., and Can, E. (2005). High-resolution surveys for geohazards and shallow gas: NW Adriatic (Italy) and Iskenderum Bay (Turkey); *Marine Geophysical Researches*, v. 26, pp. 247–266.

Volume 2 – Associated And Related Patents/Publications By The Author

Guigné J.Y., Welford J.K. & McDermott I.R. (2010). Volumetric, Multi-fold Acoustic Interrogations Of Complex Sub-seabeds, Near Surface, *EAGE*, Zurich.

AN ADAPTION OF THE ASI FOR DEEP EARTH IMAGING

“Acoustic Zoom Is Seismic For Characterizing The Non-specular Attributes Of Reservoirs”

Acoustic Zoom (AZ) is a novel seismic exploration/exploitation technique adapted from the ASI’s stationary beam-forming interrogating protocols, which holds potential for high resolution imaging of geological structures. This is achieved by using deep-penetrating, beam-formed, and beam-steered seismic signals.

The Acoustic Zoom methodology was conceived, introduced and patented by J.Y. Guigné and N.G. Pace in 2007⁹. The method employs purpose-designed steerable phased arrays, analogous to the arrays used in radio astronomy, for both the source and receiver arrays. Figure 81 illustrates this adaptation of the ASI approach.

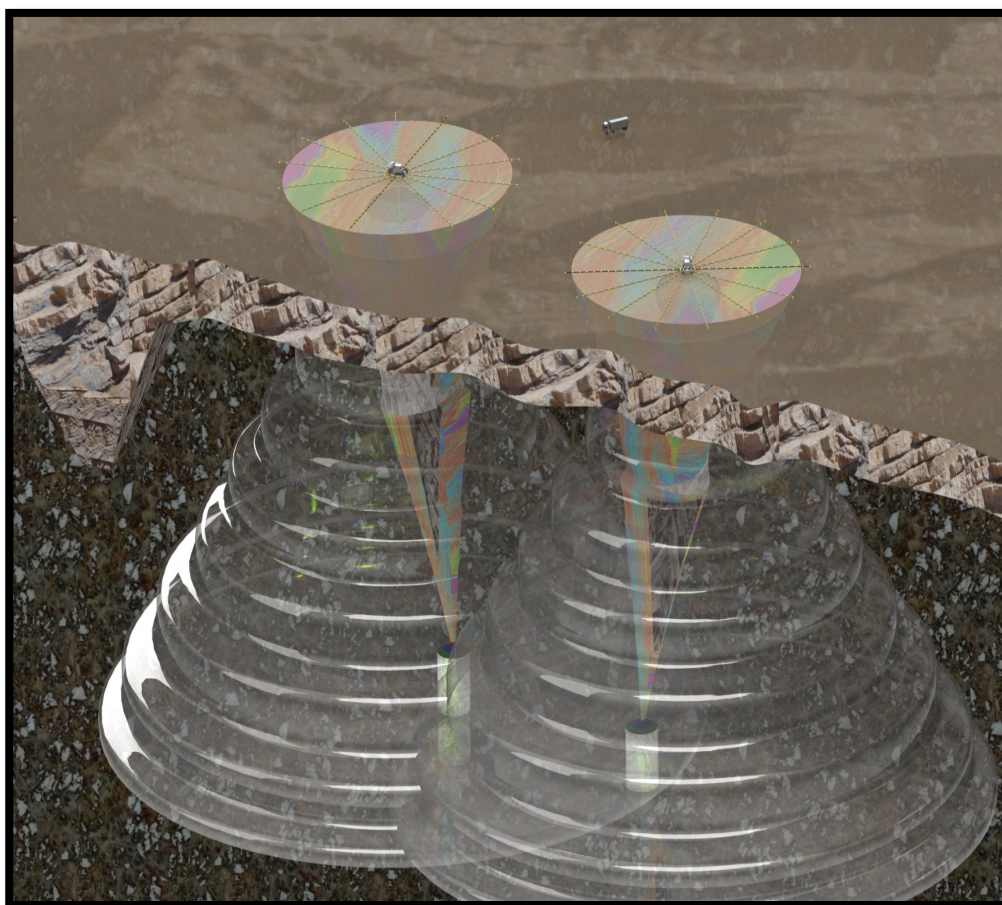


Figure 81: Conceptual drawing of the beam-forming and steering deep into the earth.
Source: Personal conceptual drawing for Acoustic Zoom Inc., November 2012

⁹ The research and development of the methodology, refinement of the protocols, formulation of the beamformers and associated synthetic modeling along with the underpinning software for processing and visualizing the data are being pursued by a dedicated AZ team led by J.Y. Guigné and composed of A. Gogacz, C. Clement, J. Stacey, A. Pant, B. Hunt, G. Dinn, T. Fleure, and N.G. Pace.

5.1 Higher Frequencies at Depth

Acoustic Zoom seismic is a seismic exploration/exploitation technique adapted from sonar applications that enables high resolution imaging of geological structures using beam-forming and beam-steering techniques. The method employs purpose-designed steerable phased arrays, analogous to the arrays used in radio astronomy, for both the source and receiver arrays. The higher resolutions attainable in the method are derived from its use and reliance on having a densely clustered, high-frequency seismic capture from a specially modified, high-fidelity vibroseis source.

This seismic source is tuned to deliver higher frequency energy sweeps, in a stacked mode, than are conventionally seen in petroleum exploration. The precision of the narrow beam combined with beam-forming and steering capabilities of the resultant transmitted and received signals make possible the delivery of unprecedented volumetric cells which capture a seismic attribute of granularity, roughness, texture of a subsurface formation.

In conventional seismic surveying, the resolution is determined by a combination of the dominant frequency propagated to and from the reflector (reservoir) and by the inversion or migration algorithm(s) used to convert the time volume to a true depth volume. The Acoustic Zoom method uses high frequencies and a wide bandwidth (typically for land use, less than 5 Hz to a high of 180 Hz).

The discrimination and steering power of a broadband receiving sensor array is at the heart of purposely arranged, densely and irregularly spaced sensors. The irregularity in spacing is a function of accommodating at half-wavelength across the broad bandwidth of frequencies of interest. This spacing aids in preventing aliased delivery of the high vertical and high lateral resolutions.

To mitigate signal loss due to frequency dependent attenuation, the generated transmission sweep is both high frequency biased and nonlinearly modulated. Moreover, coherent stacking is then employed to boost the final signal-to-noise ratio. Unlike conventional seismic where only a few shots may be acquired per shot location, the Acoustic Zoom dataset acquires a minimum of 500 shots per shot location. The boost in S/N is therefore velocity model independent. The land source configuration consists of 5 shot locations, all within $\frac{1}{4}$ wavelength from the center of the receiver array.

5.2 Unique Configuration Spread

The Acoustic Zoom seismic approach for land applications typically employs a vibroseis source together with a receiver array consisting of a randomized areal placement, spiral formation, or a number of “arms” in a star “hub-and-spoke” configuration (refer to Figure 81, which illustrates this latter type of receiver spread). The design of the array is optimized for the depth and extent of the targeted formation.

For illustrative purposes, the star receiver array configuration involves sixteen spokes at 22.5° increments, with each spoke having more than 120 discrete vertical-component sensors (3-component acquisition can also be considered) at sub-wavelength spacing, over a total spoke length of about 2000 m (120 wavelengths are required, spanning 50 Hz to 200 Hz). The aperture thus created is essentially circular, of approximately 4km in diameter, and of a size that has the near-field of the array extending to thousands of meters depth, well beyond the zone of interest.

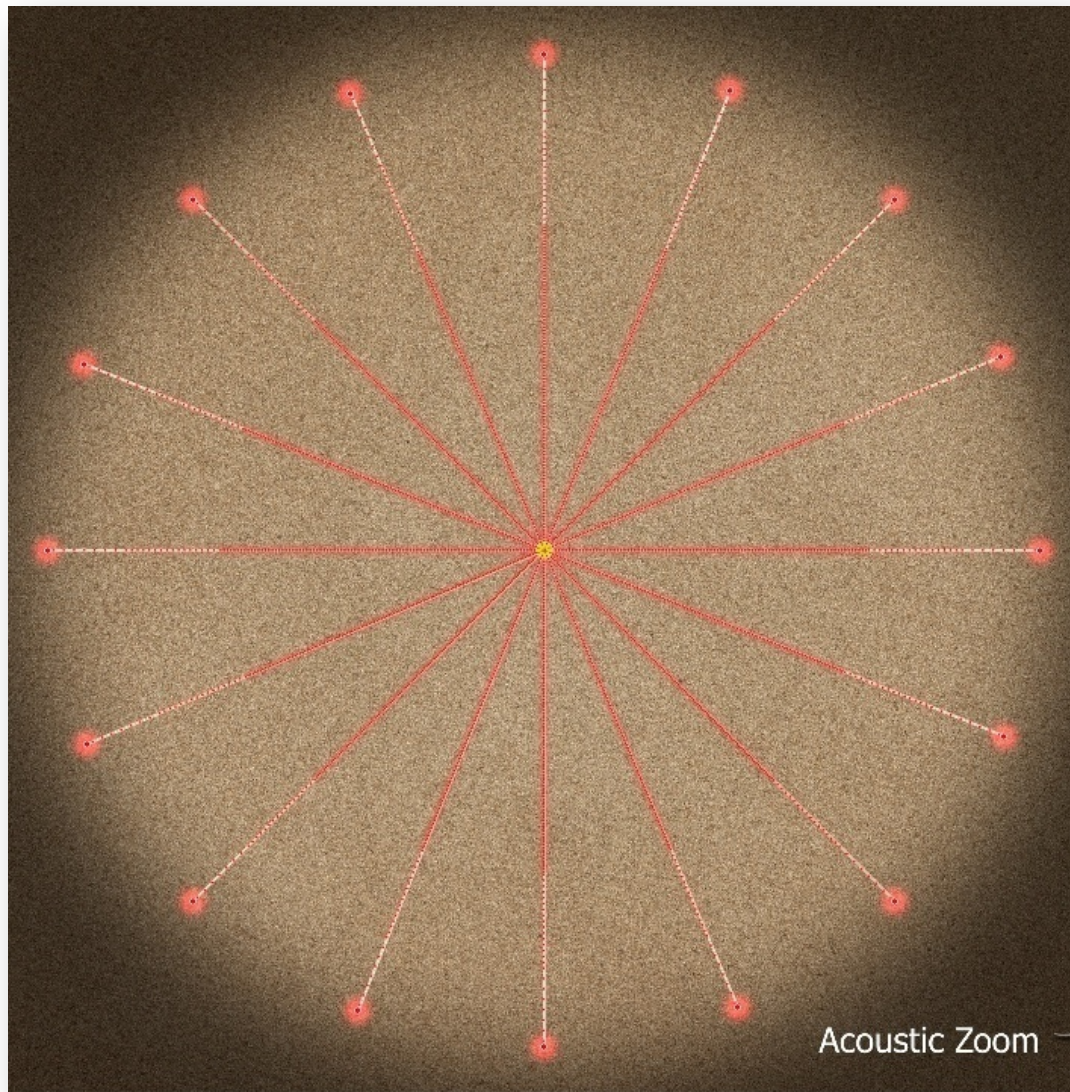


Figure 82: Pictorial of a typical receiver array configuration. Source: Personal conceptual sketch, 2007

The method is flexible to accommodate the inevitable realities encountered in laying out the array and can even benefit from placement variations of the receiver sensors as long as the wavelength spacing constraints are obeyed.

With the source and receiver arrays stationary, the effectiveness of the receiver and transmitter spread allows for coherent stacking, which rests solely on the repeatability or high fidelity of the source signals at the higher frequencies being propagated. The resultant diffused seismic data can then be focused with the sharpening of discrete half-degree beams (formed on reception). These narrowed beams provide for improved discrimination against energy arriving from internal earth volume reverberations, generally viewed in conventional reflection seismic as coherent noise.

5.3 Processing of Signals Involves Beamforming and Beam-steering

Once the seismic data has been stacked to a prescribed signal-to-noise ratio, the processing commences. Processing of Acoustic Zoom® data simulates movement of the

array through coherent in-phase beamforming and beam-steering techniques, as is widely used in phased radio antenna applications, non-destructive testing, medical imaging, and military applications. The combination of signals from individual sensors is focused into steered beams through either additive or multiplicative schemes.

The images thus formed at a given location will have as many independent points as there can be independent beams formed. The number of independent beams and thus the size of the spot or voxel corresponding to an independent beam are controlled by the aperture of the array and by the dominant frequency of the recorded signals.

A notable distinction in this method over conventional seismic methods is that each image voxel is formed only by the energy backscattered in the direction of the corresponding beam. The image does not rest on the ability to use only specular reflected energy. Thus, the image can be built from a wide range of backscatter angles, approaching $\pm 45^\circ$.

As in the radio astronomy analog and in contrast to conventional seismic surveying, the beam can be steered to look beyond the footprint of the array (see Figure 83).

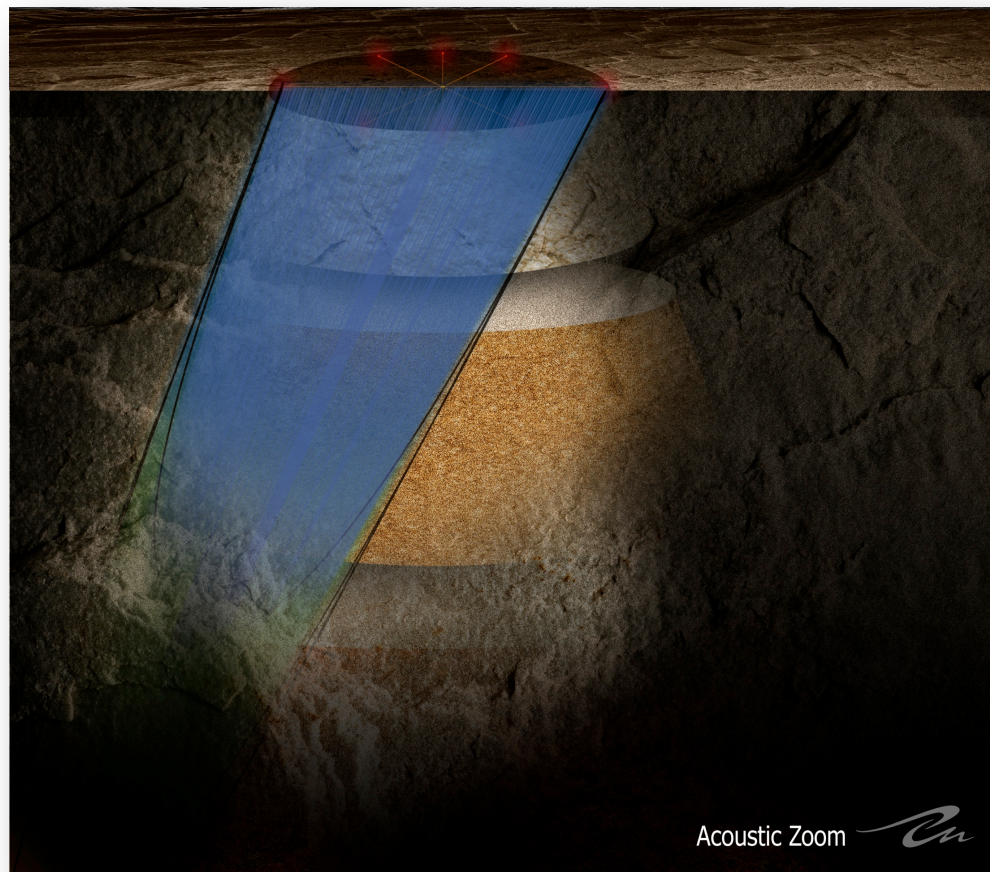


Figure 83: Pictorial of wide angle steering with an array smaller in size. Source: Personal conceptual sketch, 2007

This wide-angle steering ability means that the array can be smaller in size and still have the ability to investigate large lateral ranges and depths compared to conventional seismic arrays where the volume of investigation is constrained to lie (well) inside the bounds of the footprint of the array placement area.

A full range of beamforming and steering can be established for clusters of sensors in the array leading to further discrimination and opening the potential separation in subsequent attribute analysis. The transmission approach follows the ASI synthetic aperture sonar implementation to form a large aperture on transmission from the movement of a single source, in this case a vibroseis source. The receiver implements a radio antenna phased array.

Figures 84 and 85 illustrate these two distinct and complementary approaches along with a sketch of the beam-former application.

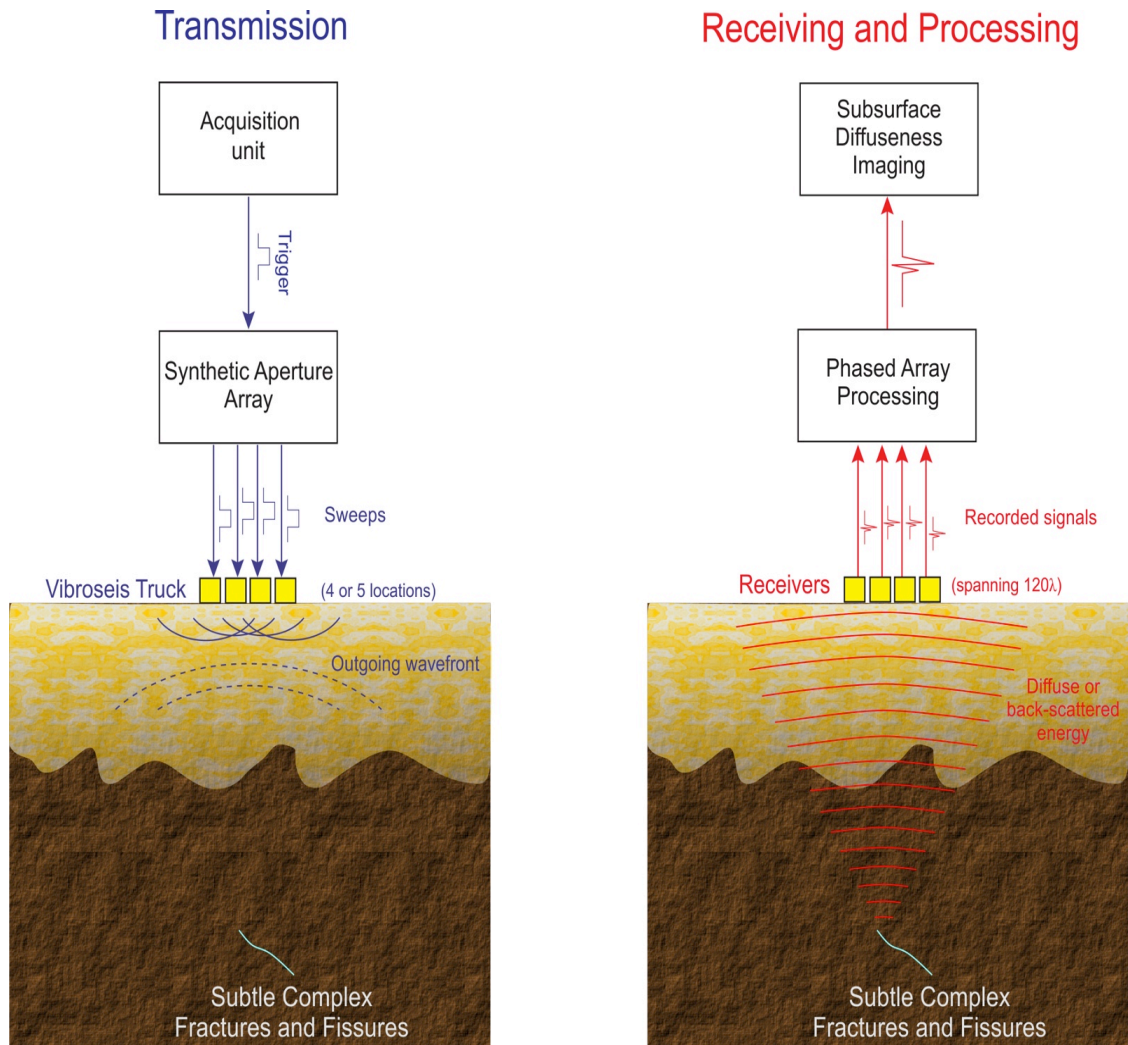


Figure 84: Graphic presentation of the transmission and reflective approaches. Source: Acoustic Zoom Inc. in-house explanatory drawings, 2011

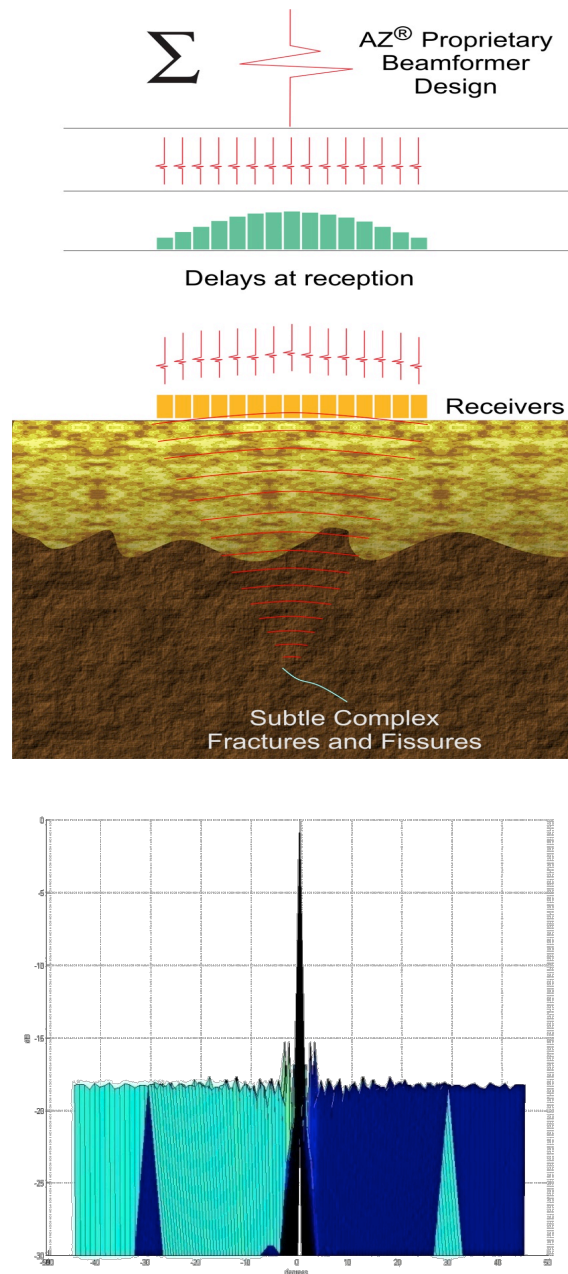


Figure 85: Graphic presentation of the beam formation (top); the bottom pictorially presents a simulation of the 0.5° resulting narrow beam width at -3 dB with side lobes 15 dB below the main beam for the AZ 120 wavelength based array for 16 radial spokes. In theory, AZ beam-forming results should provide for an additional 36 dB gain, over the incoherent ambient noise. Source: Acoustic Zoom Inc. in-house explanatory drawings, 2011

5.4 Reasons for Low Resolution Seismic Captures in Unconventional Reservoirs

The AZ method focuses on achieving detailed seismic characterization at high resolution specifically within subtle complex stratigraphic and/or volumetric geometries. This contrasts with conventional seismic practises, which attempts to accentuate major stratigraphic boundaries.

As an example, seismic exploration of over-consolidated shale zones typically involves long offset data acquisition seismic spreads in an attempt to enhance subtle fractures and faults. Even with dense receiver spreads, low spatial resolving powers generally are

achieved, which do not image the internal textural structures of targeted reservoirs well. This inability to resolve, for instance, shale-sand transitions is owed to the fact that these facies are often elastically comparable, thus no major impedance contrast can be observed within the resolution cells of the seismic data collected.

In contrast to current long offset data acquisition, the AZ employs a data acquisition approach that captures and focuses on angular returns as a bias to deliver a more comprehensive dataset with increased dynamic range, which aids in being able to characterise the subtle impedance boundaries between varying geological based strata.

This is made possible by delivering intensively stacked, high frequency vibroseis energy, deployed in a tight acoustic lens pattern that focuses source energy. The associated star-configured receiver array deployment and pattern then functions as a collector such that all of the seismic energy reflected back from the earth's structure to the receiver array is captured, especially the diffused energy. This diffused contribution, though often very weak in signal strength, is available for image processing (see Figure 86).

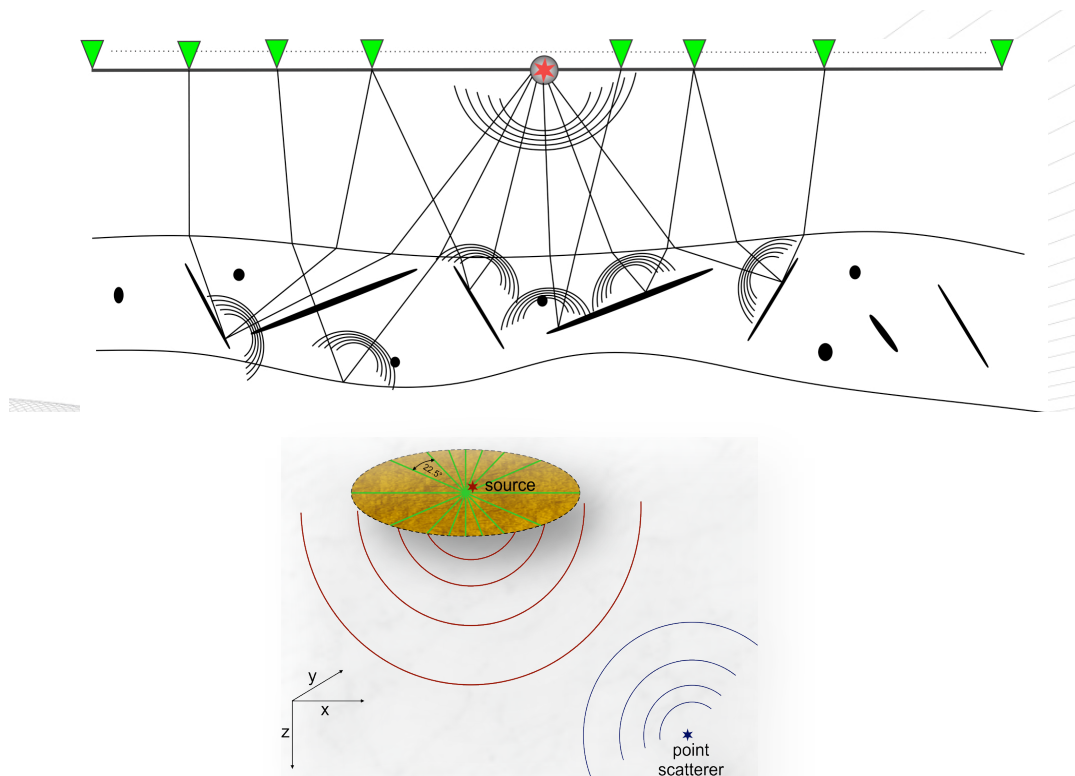


Figure 86: Graphic presentation of the diffuse scattered data collection. Source: Acoustic Zoom Inc. in-house explanatory drawings, 2011

This is a major difference between the Acoustic Zoom technique and that of conventional seismic imaging, which uses only the specular reflected energy to form the image of the geology (as noted in Figure 87).

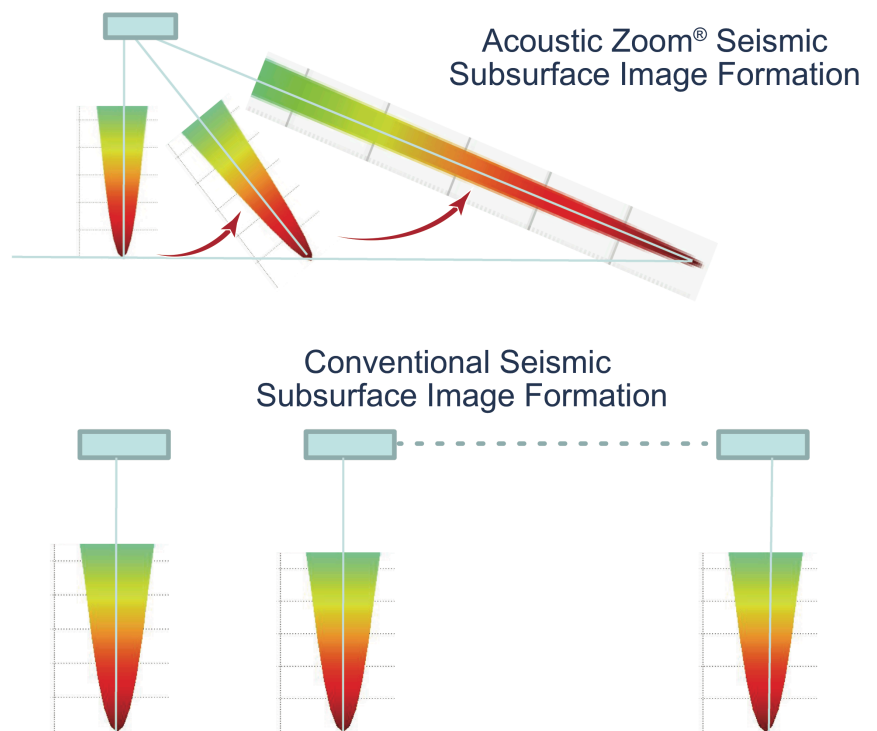


Figure 87: Graphic presentation that compares the AZ angular image approach against typical conventional seismic. Source: Acoustic Zoom Inc. in-house explanatory drawings, 2011.

Indeed, conventional migration seismic data processing inversion protocols discriminate against the diffuse, non-specular backscattered energy by their very nature of laterally stacking out the incoherent character of diffused energy.

In many instances, the very detail of the geological structure that is being imaged is too small (sub-wavelength scale) for a strong specular reflection to be built up and the detail in the reservoir is thus not resolvable. It is in these very small, but often strong, diffused, non-specular reflections that the true character of unconventional reservoir geology can be revealed.

This essentially is what the AZ beam-steering receiver and high frequency high-fidelity source transmissions can capture and beam-form onto.

5.5 High-Fidelity Of The Signals Required

With the source and receiver arrays stationary, the effectiveness of coherent stacking rests solely on the repeatability and high fidelity of the source signals at the higher frequencies being propagated. The resultant seismic data can then be focused with the sharpening of discrete half-degree beams (formed on reception) providing significant discrimination against energy arriving from internal earth volume reverberations, generally viewed in conventional seismic as coherent noise.

Once the seismic data has been stacked to a predetermined signal-to-noise ratio, the field work is complete, and the processing commences. Processing of Acoustic Zoom seismic data simulates movement of the array through coherent phase beam-forming and

beam-steering techniques (as is widely used in phased radio antenna applications). Figure 88 presents the principle of focusing.

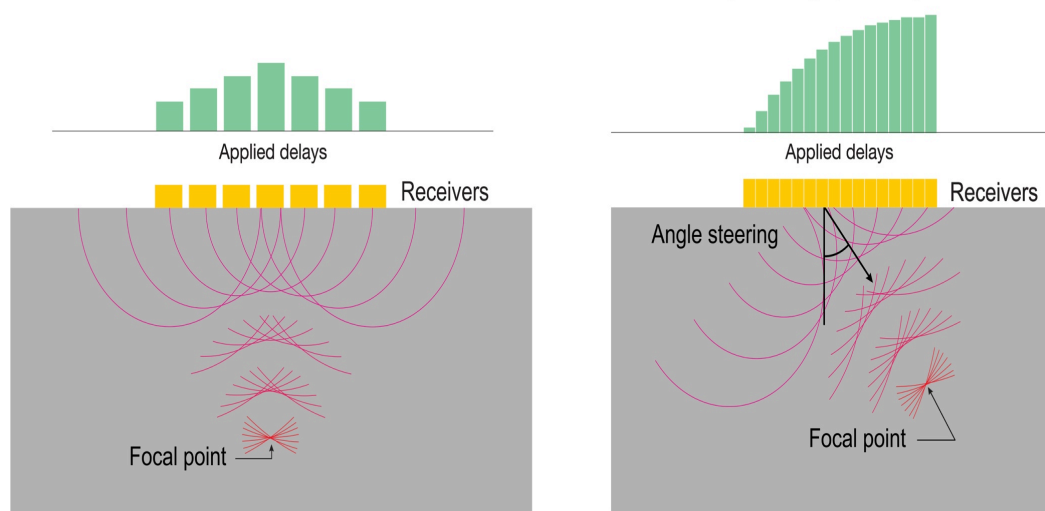


Figure 88: AZ beam focusing principle for normal and angle impinging wavefronts, illustrated via emission and reciprocity principle. Source: Acoustic Zoom Inc. in-house explanatory drawings, 2011

The combination of signals from individual sensors is focused into steered beams through either additive or multiplicative schemes. The images thus formed at a given location will have as many discrete points as there can be independent beams formed. The number of independent beams, and thus the size of the spot or voxel corresponding to an independent beam are controlled by the aperture of the array. This is accomplished entirely in the data set through software processing of the recorded data.

5.6 Complementary To Existing 3D Seismic

The techniques of higher frequency arraying and beam-forming can be used to enhance overall seismic resolution to enable a more comprehensive structural imaging of the reservoir and surrounding geology's sealing faults, stratigraphic pinch outs, facies, and micro-faulting variations. The AZ array approach is designed to obtain spatial resolutions that are not only a factor of 5–10 improvement over conventional 3D seismic at the same depth but also will deliver on the rich non-specular aspects of the geology.

It is the intent to have the Acoustic Zoom seismic implementation to be guided by the detailed geological model that would exist for a region and surrounding geology that has been developed through conventional 3D depth imaging analysis and from well bores, very much like the implementation of the ASI with boreholes and in situ penetrometer tests. Since a coarse structural model is “known,” then the prime focus of AZ is on the seismic attribute changes due to subtle geological stratigraphy changes, diffractions and micro faulting.

The assumption of the structural geological model (velocity model) allows considerable *a priori* knowledge to be used to guide the beam-steering. After AZ produces its high-definition data set, including the focused velocity values through the Acoustic Zoom method, then this high definition localized data could be “rubber banded” into existing seismic data sets.

The Acoustic Zoom data produced at formation depth delivered imagery that would be composed of multi-aspect intensity results from the sweeping of the AZ beams. The resultant display from such multi-views would exhibit a more textural data character than that possible from conventional seismic surveys, taking on imagery that would resemble more of the true internal “textural” construct of the formations, accentuating the backscatter nature of the energy redistribution.

This is in direct contrast with conventional migration based data presentations, which accentuates in its renderings only coherent reflection-based returns, filtering out the discontinuities or “noise.” It is these discontinuities that are so rich in information because they reveal strategic internal textural information.

5.7 What Has Been Accomplished To Date

The experimental development of the Acoustic Zoom method is a work in progress. An in-depth evaluation of the AZ signal propagation in a realistic sedimentary basin is underway.

The development of the protocols to form and steer source and receiver beams in the data space, and to assess the ability to identify anomalous return signals associated with the characterization of typical petroleum reservoirs, are complex tasks that require rigor in their underpinning physics, in the design, and in the models that underpin the method. Hence, the fundamental assumptions of the method require an iterative validation and verification from several actual site experiments to test assumptions.

An experimental study was initiated in 2010 to address the science uncertainties or assumptions in the AZ data acquisition and signal processing and analysis. For instance, what are the issues in the propagation and processing of high frequency seismic signals especially when coherent stacking of signals is involved over many cycles? What geological structures would be pertinent for investigation using the AZ method? Can high frequency biased sweeps still return with much higher and broader spectral content than is observed in conventional surveys? Can we rely on coherent signal stacking to enhance signal detection to the desired signal-to-noise levels?

There are also risks that relate to the level of control and repeatability of the seismic source wave shape and frequency content that would in practice be able to be achieved. Good coupling of the source to the earth, delivering the power into the ground are always problematic and are additional points to consider.

In an attempt to tackle these questions in an experimentally deterministic manner, a series of field tests were conducted in Houston, Texas on July 19–20, 2010, at the ExxonMobil Friendswood upstream experimental research site. The data acquired at the test facility were wholly intended for scientific examination of the spectral content with depth and to confirm the coherency of the source signal. A modified vibroseis truck capable of generating such targeted higher frequencies was employed as a practical starting point (refer to Figures 89, 90 and 91).



Figure 89: High frequency source testing at the ExxonMobil Friendswood Experimental test site in Houston, Texas. Source: Pangeo Subsea Inc. internal interim report to ACOA – AIF research project and to NRC- IRAP project, 2010



Figure 90: J.Y. Guigné and A. Gogacz at the ExxonMobil Friendswood Experimental test site in Houston, Texas. Source: ACOA –AIF and NRC-IRAP Interim Reports, 2010



Figure 91: Photograph relates to vibrating plate of the vibroseis truck, which was modified to generate stable higher frequencies, and the pads under the plate of the truck, to better couple the vibrations to the earth. Source: ACOA –AIF and NRC-IRAP Interim Reports, 2010

Of particular importance, the tests were designed to determine whether the nonlinear sweep signals were sufficiently stable for the AZ data acquisition and processing methodology. Of equal importance was the determination of attenuation of the source signal and the coherence of the source wavelet when generated within a spatially limited region.

The analyses carried out revealed that the coherence of the source signal did not degrade with continual sweep generation. Analyses of the spectral content showed that at target depth of 1000m, high frequencies of over 100Hz were observed for the 2 and 4 dB nonlinear sweeps. Analyses of signal to background noise revealed that at the site the 2 dB sweep produced an overall more suitable and reduced noise response. Additionally, the analysis carried out indicated that within a spatially limited region variation of the source location did not produce any undesirable phase and power fluctuations.

5.8 First Full-scale AZ Land Pilot

In November 2011, a full-scale AZ field pilot investigation was accomplished on a strategic over-consolidated shale formation (unconventional reservoir). The site is related to the Eagle Ford formation, which is considered to be an economically rich structure with vast entrapped gas and condensate potential, in the region of San Antonio, Texas. A 12.5 sq. km area was imaged as part of Global Geophysical Services' Wrangler 3D multi-client survey in Wilson County Texas over the prolific Eagle Ford (shale), Austin Chalk (chalk), and Buda (limestone) formations. Figure 92 is a county land plot with the AZ footprint superimposed to show the distribution of its 16 radial lines, each 2 kilometers long. Over 4000 receiver group locations with six buried geophones per receiver group were planted and accurately located (see Figure 93).

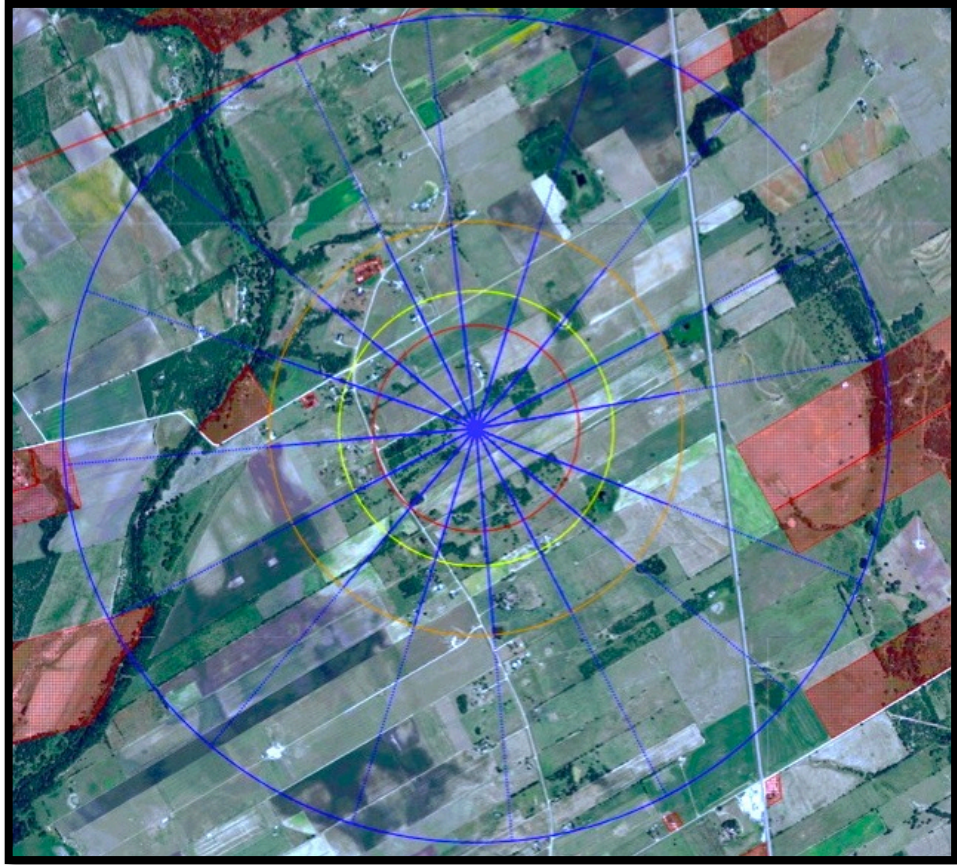


Figure 92: Field county land plot for first full scale AZ pilot in the region of San Antonio, Texas. A 12.5 sq. km area was AZ imaged in November 2011. Source: Global Geophysical Services Inc. field photograph (released to Acoustic Zoom Inc. with permission) with AZ receiver footprint, 2011.

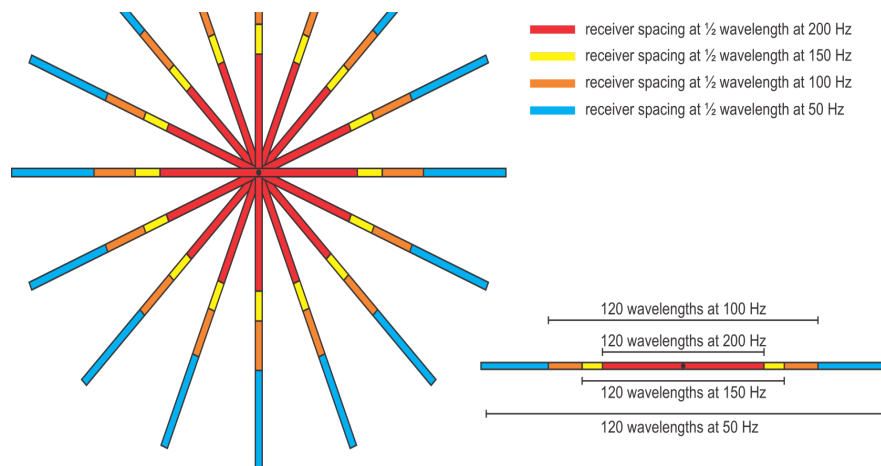


Figure 93: Layout script used to distribute the 4000 receivers with specific spacing as per the 120 wavelengths at associated frequencies of up to 200 Hz. Source: Acoustic Zoom Inc. in-house field preparation notes, 2011

Over two terabytes of data were acquired using the AZ custom array of 4000 receivers with captured frequencies of up to 170 Hz were recorded. The apex of the receiver array is noted in the photograph of Figure 94.



Figure 94: First full scale AZ pilot in the region of San Antonio, Texas. A 12.5 sq. km area was imaged as part of Global Geophysical Services' Wrangler 3D multi-client survey in Wilson County Texas in November 2011. In the picture: C. Clements, J.Y. Guigné, and A. Gogacz stand at the apex of the AZ receiver star array. Source: Acoustic Zoom Inc. in-house field photographs, 2011

Figure 95 presents the general character of the terrain where the geophones were planted. The topsoil is composed of loose, brown, silty clay overlying more consolidated stiff red clay.



Figure 95: Terrain on which the geophones (in orange) were implanted in the region of San Antonio, Texas. Source: Acoustic Zoom Inc. in-house AZ first pilot field photographs, 2011

Five vibe locations were established at $\frac{1}{4}$ wavelength separation, in a cross configuration (see Figures 96 and 97). Figure 97 presents an actual photograph of the Vibroseis truck as placed in the excavated cross where the orange-sprayed dots demarks the $\frac{1}{4}$ wavelength separation locations.

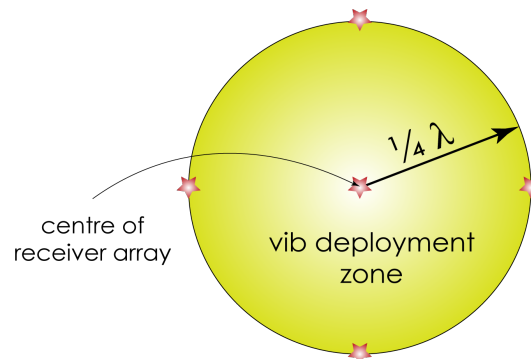


Figure 96: Vibroseis truck placement with 5 source locations, 4 sources on the $\frac{1}{4}$ wavelength perimeter and 1 source at or near the centre of the receiver array. Source: Acoustic Zoom Inc. in-house AZ first pilot field placement sketch, 2011

The ground was prepared by removing the loose brown topsoil, using a bulldozer to access the hardness of the underlying red clay, which was “like concrete” and acted as a good coupling medium for the vibrator. 512 sweeps were generated and stacked at each of the five vibroseis locations.



Figure 97: Vibroseis truck placed in the excavated cross. The loose brown clay was removed to reveal a concrete hard red clay basement. Source: Acoustic Zoom Inc. in-house AZ first pilot field photographs, 2011

The data acquisition was controlled within a dedicated data van which allowed the signals to be configured and quality verified for phase changes and errors associated to the generation and reception of the signals (see Figure 98). The final positions of the receiver array locations can be seen on the screen on one of the monitors and is highlighted in Figures 99 and 100.



Figure 98: Data Acquisition Van. Source: Acoustic Zoom Inc. in-house AZ first pilot field photographs, 2011



Figure 99: Data acquisition truck and signal quality operations. Source: Acoustic Zoom Inc. in-house AZ first pilot field photographs, 2011

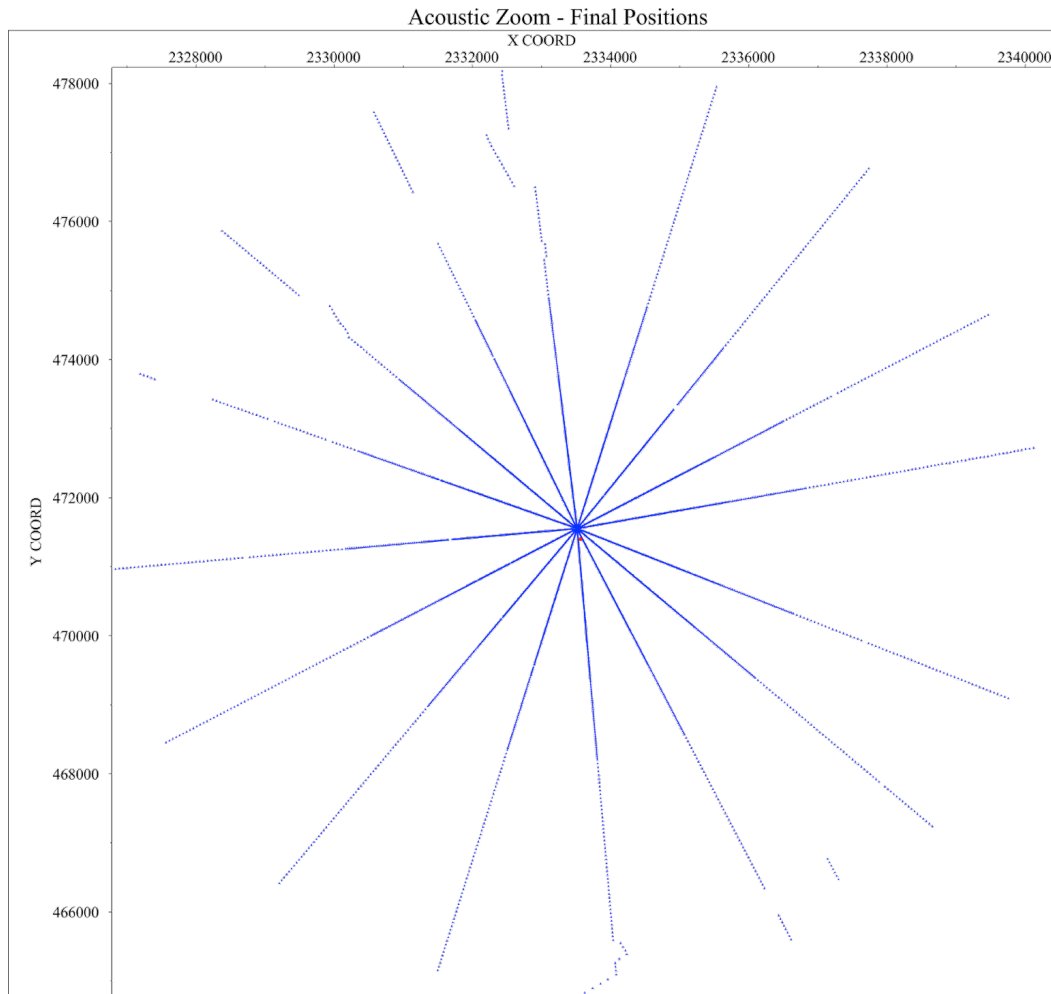


Figure 100: Final sensor location plot. Source: Acoustic Zoom Inc. in-house AZ first pilot, sensor field location printout, 2011

5.9 Preliminary Results

The analysis of the pilot data has started and of importance was to examine evidence for higher frequency signals at the Eagle Ford formation than what typically could be attained from conventional seismic acquisitions and processing for the area imaged.

Figure 101 relates to the final sweep showing evidence for high frequency at formation depth. This contrasts with a representative conventional seismic plot taken at the same location with a typical max. 70Hz frequency (see Figure 102).

The signals transmitted and acquired stacked coherently. As an example of the output of the stacking, Figure 103 illustrates the results of vertical stacking folds of 1, 200, 300, 400, 512, for two of the five vibroseis locations.

The ambient noise shows a flat power spectral density; an exponentially decaying power spectral density function is associated with the transmitted signal. No substantial gains are made beyond a 400-fold stack, within the window of analysis. At the transitional region, within the power spectrum, from signal curve to noise floor, the general rule of \sqrt{N} signal-to-uncorrelated noise gain holds and is exceeded for a number of lines.

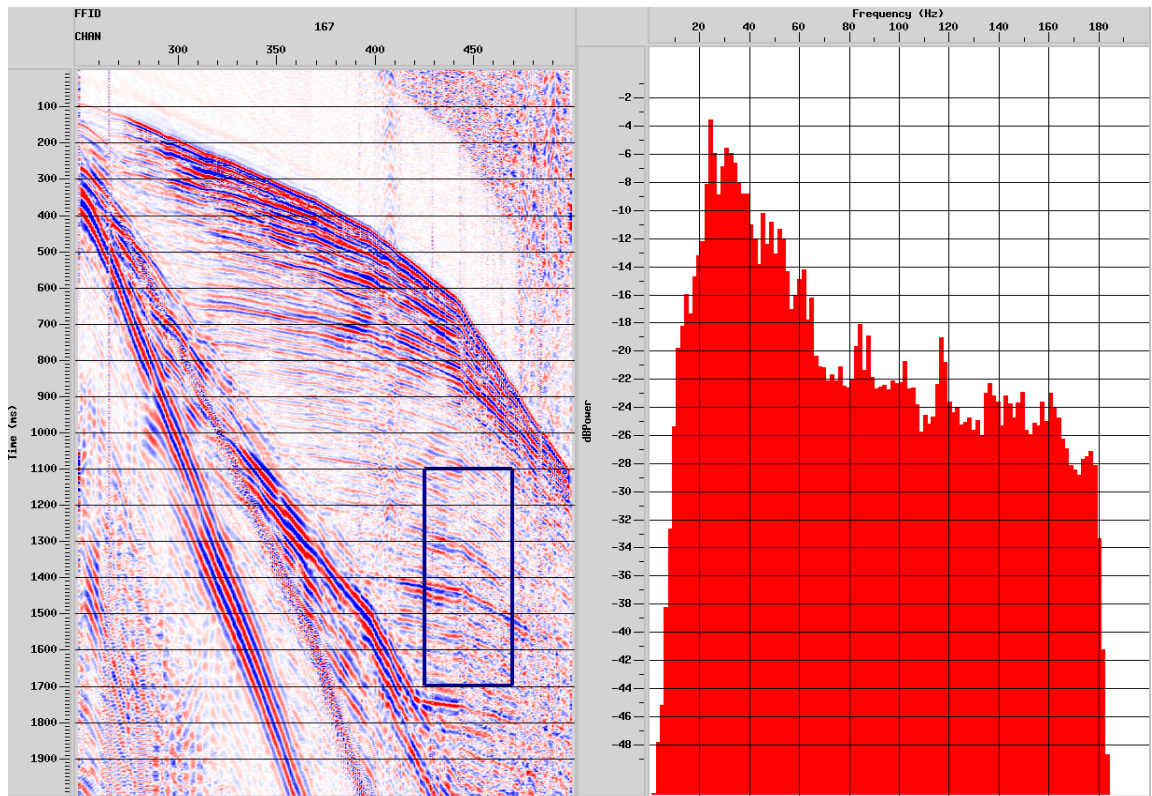


Figure 101: Final sweep definition: 170 Hz, 2 dB/octave pre-correlation slope, 40 seconds duration with a 50% drive-level. The frequency plot is at the Eagle Ford formation. Source: Acoustic Zoom Inc. in-house AZ first pilot, sensor field location printout, 2011

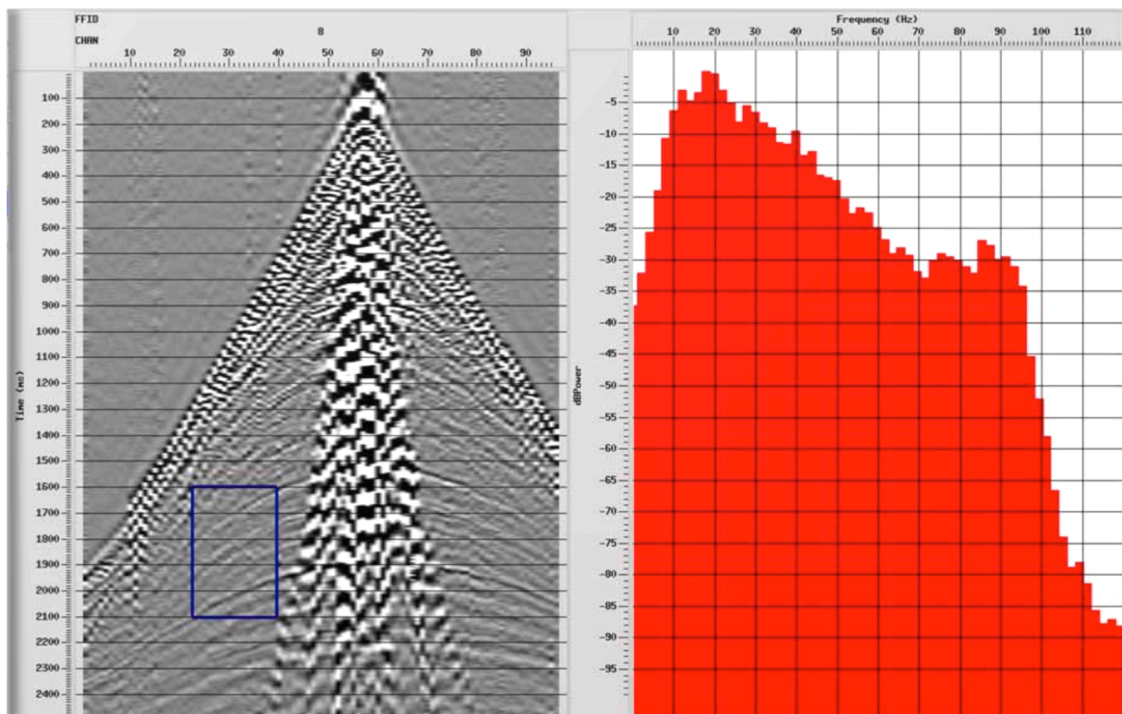


Figure 102: Actual conventional seismic sweep at the Eagle Ford formation where the pilot took place with a definition of 6-96 hz, 1 dB/octave pre-correlation slope, 24 seconds duration and a resultant max 70 Hz typical frequency sweep peak. Source: Global Geophysical Services internal data plot, 2011

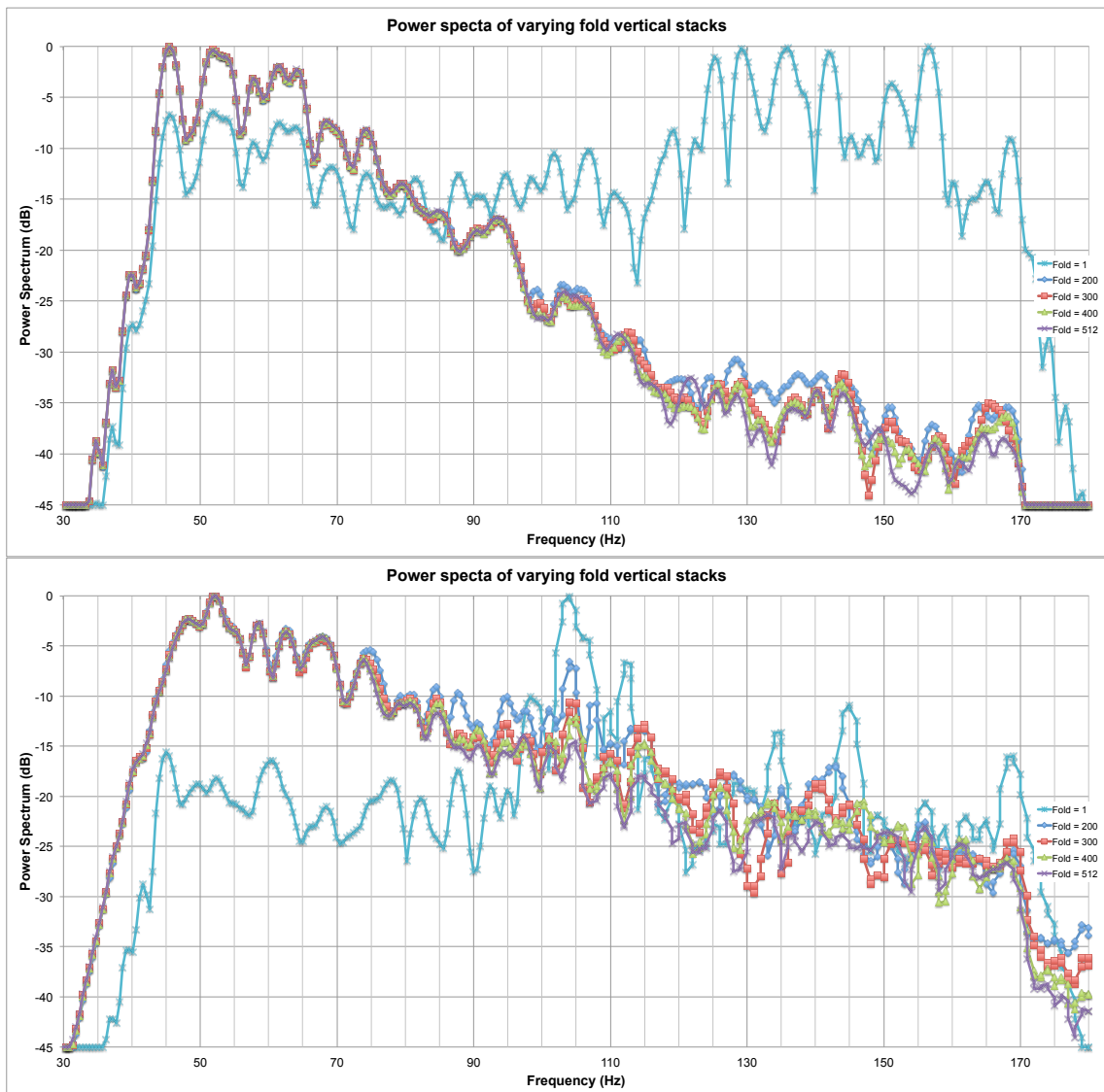


Figure 103: Vertical stacking folds of 1, 200, 300, 400, 512, for two of the five vibroseis locations Source: Acoustic Zoom Inc. in-house AZ first pilot preliminary analysis plots, 2012

As a first look at azimuthal frequency distribution at 1.5 second, the time spectral content estimations, based on spectral dispersion, indicate that at the Eagle Ford formation of interest, which is approximately 1.5 second (two-way travel time), and mid-offset range of approximately 2,250 feet vertical summation, “brings-out” frequencies exceeding 140 Hz above the ambient noise floor; this is graphically revealed in Figure 104.

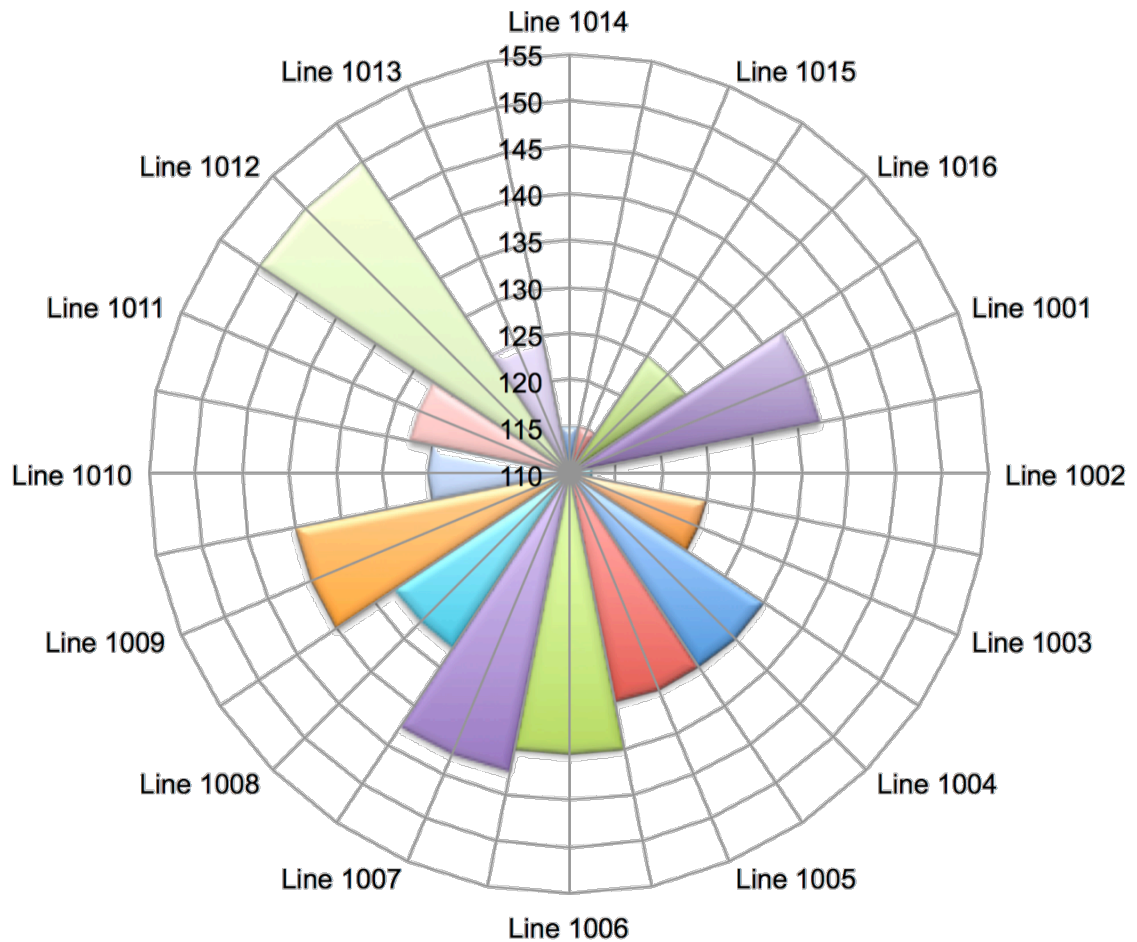


Figure 104: First look at azimuthal frequency distribution at 1.5 second two way travel time, with frequency parameterized along radial lines, heading of each acquisition line represented angularly and each radial line represented by distinctly colored sector. Source: Acoustic Zoom Inc. in-house AZ first pilot preliminary analysis plots, 2012

Analysis of the pilot data is continuing. Coherent beam-forming with an aperture of over 4,000 receivers over the five vibroseis locations is being considered. It is expected that this will further reduce the S/N by a factor of 43 dB. The beam-forming will also improve the Signal to Coherent Noise and/or Volume Reverberation.

5.10 Value proposition Application Directions

There is a growing interest and an extensive set of publications relating to new protocols for acquiring and analyzing seismic data, to investigate the best way to manage diffraction conditions in the earth and the various ways to handle velocities influenced by diffractions (e.g. Keydar, 2004; Sava, 2005; Novais, 2006; Fomel, 2007; Schleicher & Costa, 2009; Al-Dajani & Fomel, 2010). Acoustic Zoom has the potential to apply these routines and characterize unconventional petroleum reservoirs at a resolution that is about an order of magnitude greater than current seismic technology.

AZ may provide characterization data in a rapid operational timeline, eliminating the cost and risk associated with the typical 6–12 month timeline as in the delivery of conventional 3D seismic results. The high resolution of AZ will also help bridge the recurring problem of linking seismic resolution with well-log resolution.

Establishing realistic performance targets for the AZ applications are especially important given that a key goal is to delineate fine internal structure of petroleum reservoirs that often control the oil and gas migration within the reservoir to the producing well. The unique non-specular datasets from the Acoustic Zoom protocols could become an essential aid in proper well design to optimize all production and injection wells. This is an extremely important quality objective to deliver on from both productivity (no by-passed pay) and safety (no breakthroughs of injected gas) perspectives. The ability to monitor fluid migration within the reservoir at higher frequencies than is currently possible with conventional seismic while under production is a very exciting breakthrough feature.

The following illustration, Figure 105, depicts the type of sector impact the Acoustic Zoom® method could have across the cycle of exploration, through to appraisal and development to production:

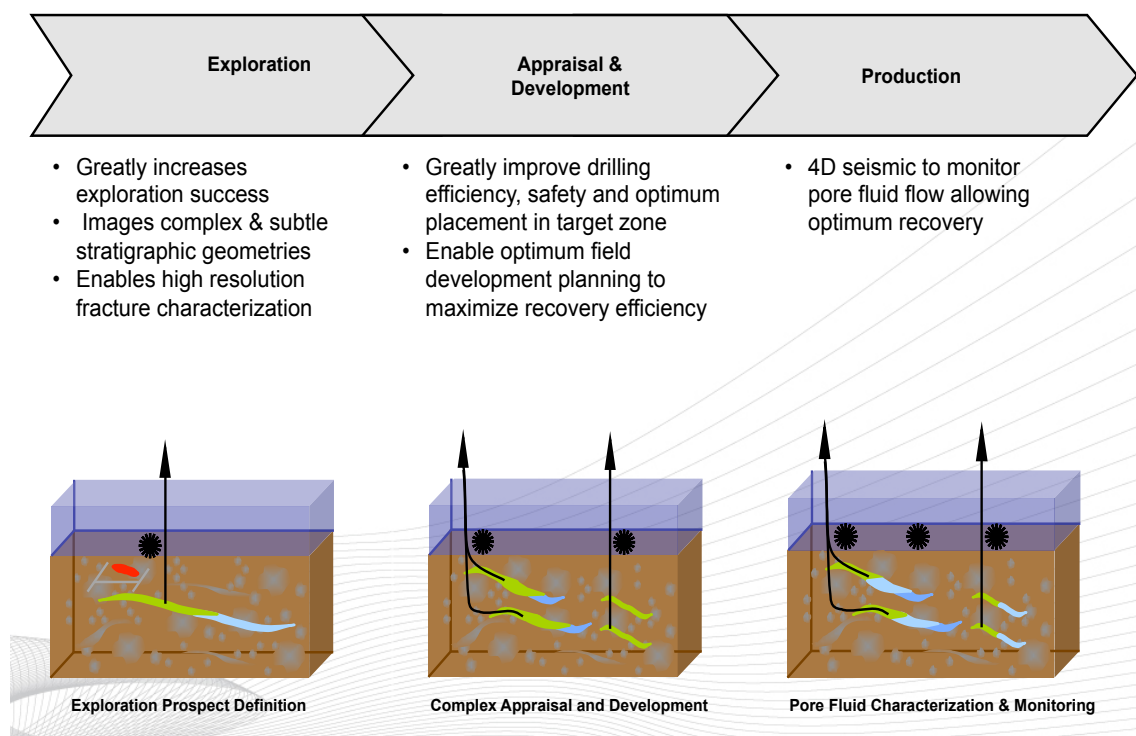


Figure 105: Applications are from exploration to production. Source: Simmons & Company International; Information Memorandum on PanGeo Subsea Inc. February, 2010.

The AZ value proposition can be thought of as delivering images and subsurface characterizations in an iterative manner complementing and enhancing conventional seismic (see Figure 106).

Its high-resolution seismic images (VSP quality) at targeted reservoir zones deliver answer products for the mapping of fluid migration in reservoirs and identification of by-passed pay zones (water-flood, steam-flood, and gas injection), for the mapping of the facies variations, natural fractures and micro-fault systems within and around the reservoir zone as a high-resolution capability to plan new and infill drilling locations, and for the mapping of open and closed hydraulic fractures created during stimulation processes.

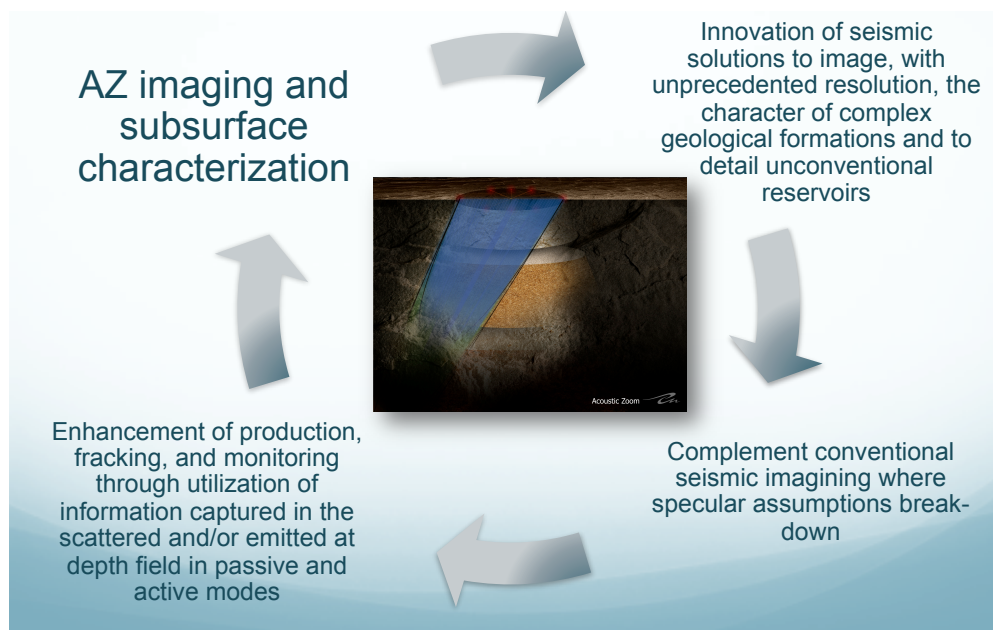


Figure 106: Acoustic Zoom imaging and subsurface characterization pictorial. Source: Acoustic Zoom Inc. in-house AZ value proposition diagram, 2012

In summary, whilst still being evaluated, the Acoustic Zoom stationary source and receiver antennae deployments and processes are an attempt at extending the ASI methodology deep into the earth for reservoir characterization. Preliminary results suggest that, like the ASI, the data-driven (all pass) incoherent noise suppression with the signal at reservoir depth can be achieved and built up before imaging.

The push to deliver higher frequency energy deep should allow for higher detailed reservoir characterization and velocity model refinement including getting at scales that best match the heterogeneities, roughness, and non-depositional discontinuities typically found in tight oil formations. Knowledge of the diffuse field (i.e. fractures, fissures, boundary roughness, heterogeneities) aids in prospect evaluation and fracking. Hence the Acoustic Zoom should provide not only potential for superior high resolution localized image of these attributes, but also the potential for 4D pseudo, real-time processing of the data.

Economically, the minimal infrastructure yet high efficient, low cost, sparse array, is commercially attractive when considering the outlay required for conventional seismic imaging at the reservoir depth. Ultimately any method that is capable of delivering higher resolution images than typically seen in conventional land and/or marine seismic surveys is of tremendous value.

References Cited

- Al-Dajani, A., & Fomel, S. (2010). Fractures detection using multi-azimuth diffractions focusing measure: is it feasible?. *80th Annual International Meeting, SEG, Expanded Abstracts*, 287–291.
- Fomel, S., Landa, E. & Taner, T. (2007). Poststack velocity analysis by separation and imaging of seismic diffractions: *Geophysics* (72)6, U89–U94.
- Guigné J. Y. (1986). *The concept, design and experimental evaluation of 'acoustic sub-seabed interrogation.'* Ph.D. thesis, University of Bath, Bath, England.
- Keydar, S. (2004). Homeomorphic imaging using path integrals: *66th Annual International*

Conference and Exhibition, EAGE, Extended Abstracts, P078.

Liu, Y., S. Fomel, & G. Liu, (2010). Nonlinear structure-enhancing filtering using plane-wave prediction. *Geophysical Prospecting* (58), 415–427.

Novais, A., Costa, J., & Schleicher, J. (2006). Velocity determination by image-wave remigration: *68th Annual International Conference and Exhibition, EAGE, Extended Abstracts, P157.*

Sava, P. C., B. Biondi, & J. Etgen, (2005). Wave-equation migration velocity analysis by focusing diffractions and reflections. *Geophysics* (70)3, U19–U27.

Schleicher, J. & Costa, J.C. (2009) Migration velocity analysis by double path-integral migration: *Geophysics* (74) 6, WCA225–WCA231.

Volume 2 – Associated And Related Patents/Publications By The Author

Guigné, J.Y. & Pace, N.G. (2009). *US Patent No. 7,830,748.* USA Patent Office.

Guigné, J.Y. Pace, N.G., Wright, J., & Dinn, G.(2011). *US Patent Application 0075520.* USA Patent Office.

Guigné, J.Y. Pace, N.G., & Gogacz, A. (2011). *US Patent Application No. 0317518.* USA Patent Office.

THE FUTURE FOR “ACOUSTICS IN THE SEABED”

“The Next Chapter”

6.1 Filling in the Technology Gap

It is well recognized in geophysical literatures, that imaging of lateral stratigraphy and showing only major sedimentary changes is not always indicative of the true stratigraphic organization of sedimentary facies. Minor banding may be representative of layering or of a minor, highly localized internal sediment banding. There is a growing recognition by geoscientists that there is a need to supplement physical sampling methods by wider usage of various geophysical acoustic and seismic based surveying techniques to map the dominant sub-bottom features' specular reflective physical and behavioral properties.

These techniques generally rely on having continuity in sub-bottom formation “horizons” or layers (i.e. acoustic/seismic boundaries). However, even with today's profiler innovations the sub-bottom is not composed only of lateral smoothly varying spatial features but also include widely distributed scattering and attenuating sedimentary and bedrock features or characteristics which translate into back-scattered, diffuse, non-specular acoustic reflections. Such diffuse reflections are generally interpreted as noise and subsequently filtered out of the data by conventional processing techniques. It is desirable to have in marine geotechnical site investigations that such sub-bottom texturally induced responses be ultimately captured and visualized in a coherent manner and carried into the interpretations of sub-bottom acoustic/seismic data.

Apart from the ASI, seabed imaging techniques known in the art cannot acoustically/seismically deliver imagery of the surrounding inhomogeneous sediment conditions such as required by offshore installation engineers especially for pile or drill emplacements. Existing sonar techniques cross-reference poorly their data responses because such data are captured through continuously moving acoustic data acquisitions with sparse coverage with respect to the order of the wavelength of the intended features to be imaged.

Recapping from previous chapters, the ASI methodology that was conceived and presented in Guigné's PhD in 1986 at Bath can take on various configurations but relies on precise positional control of the transducer array on a stationary platform resting on the seabed surface. This allows for the array to coherently transmit signals with a signal having been specifically selected and programmed in terms of power, center frequency, beam-width, bandwidth, shape, and incident angle. A positional receiver array on the platform is equally controlled with precision to ensure that the seabed responses are captured coherently both for their reflections and backscatter.

Sub-surface acoustical properties, at the location of the ASI deployment, are identifiable through beam-forming from various directional aspects within the ASI platform footprint. Various geotechnical correlations can be predicted from the processed returned signals. A calculation of the speed of sound in the sub-bottom, at the site of investigation, is introduced through the use of two extra orthogonal data line collections, which apply traditional seismic data acquisition routines involving time migration protocols to calibrate the specular returns and to acquire velocity information that can be used in the synthetic data rendering routines.. Subsequently, sub-bottom positions within a selected volume can then be interrogated using well understood digital processing algorithms based on synthetic aperture sonar principles, combined with a continuously gathered, successive

transmission sequence which reliably are acquired along a precise data acquisition track in order to increase the azimuth (along-track) resolution. An interpretation is made of the acoustical reflected and backscattered properties between locations profiled to develop a distribution model of the specular and diffused properties within a sedimentary volume in the sub-bottom.

6.2 Acoustic Analysis From A Drill Stem

As discussed in Chapter 1, offshore geotechnical engineers are trained to rely on borehole and/or cone penetrometer data for marine geotechnical, shallow (first 50m of the sub-seabed) sub-bottom formation assessment. The collection of these forms of samples, both physical or cone penetrometer-derived data, is expensive and limited in its spatial representation of what is the true nature of the sub-bottom. In addition, the samples recovered may have been altered or biased during their collection.

Conventional acoustic imaging methods, which are used extensively in connection with marine drilling, coring and in situ cone sensing, remain isolated within their own prime physical interactions with the water sub-bottom. Their data uncertainties often put into question the reliability of the physical boundaries displayed in cross-sections of the samples recovered or in the interpretation of the penetrometer profiles and values. Without additional verification and multiple or dense spot sampling, such geotechnical physical samples remain in effect a one-dimensional input to site investigations.

Both lateral and discrete discontinuities within the sub-bottom are important to know for offshore engineering and construction programs to be able to mitigate installation instabilities and safety risks. These seabed discontinuities arise from complex geological sedimentary, tectonic, and glacial processes. The varying nature that characterize complex seabed conditions are factors that influence the quality and dependability of physical core retrieval. These discontinuities in the sub-bottom can take the form of soft sedimentary lenses, boulder/cobble erratics, glacial tills, hard pans, fluidized discontinuous mud layers, gas hydrates, gas-charged sediments and periglacial frozen soil features.

The resultant core samples may not be capable of capturing and retaining such materials or produce undisturbed samples thereof once retrieved at the surface. Soft sediments become compressed during core extraction and depending on the extraction conditions may fluidize some of the materials in the core sample. This means an incorrect stratigraphic interpretation could occur but such would not be known or suspected when observing the core sample.

In addition, there may be disruptive blockages in acquiring physical cores by large particulates or the inclusion of highly dense fragments. These blockages and or inclusions could be misinterpreted as belonging to a bedrock formation that does not exist at that particular depth. Without a multiplicity of physical cores taken in close proximity, the true lateral extent and nature of these boundaries may not be known.

A future embodiment for the ASI would be to provide for an extended acoustic core that is collocated with a borehole by generating the acoustics off a drill stem. A future design could see the tripod legs be removed of a typical ASI such as in the PanGeo Subsea Inc. Acoustic Corer and be replaced by a drill stem (see Volume 2 for a complete description of this "Wide Area Seabed Analysis" patent). This would not involve major changes to the ASI sounding and/or receiving data collection, nor to the processing protocols. Figure 107 illustrates this future concept.

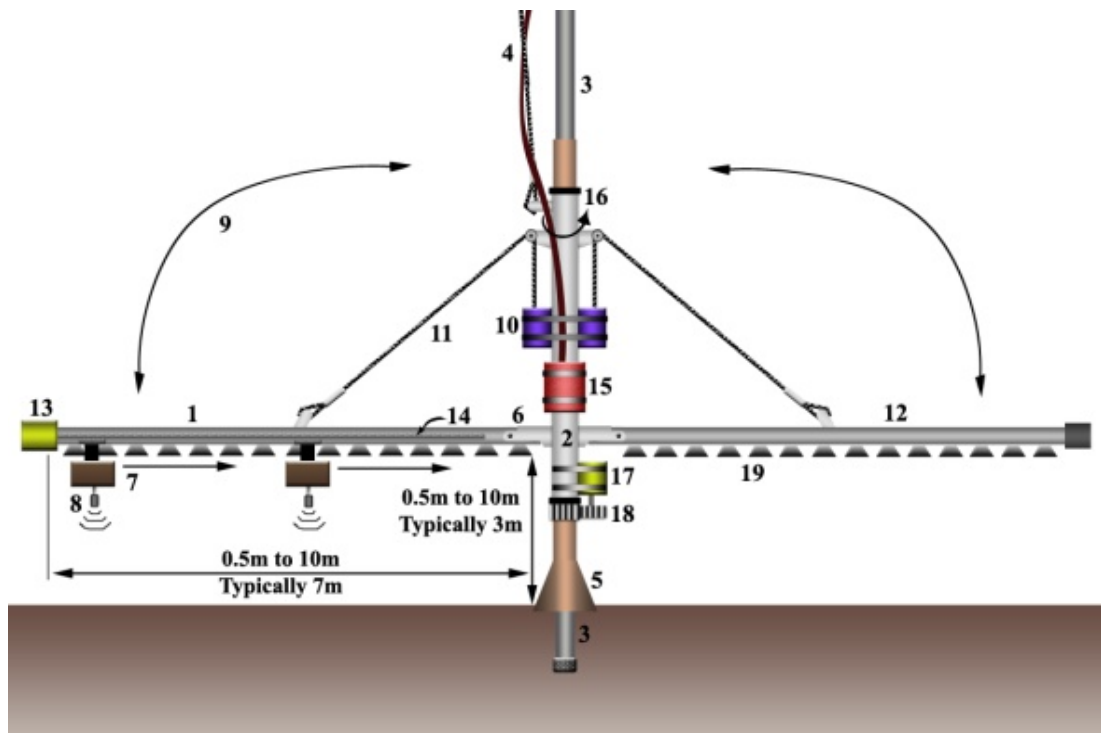


Figure 107: Application of an ASI by removing the tripod legs and replacing this by a drill stem. The drawing is in support of the patent called “Wide Area Seabed Analysis” by J.Y. Guigné; with the original drawing depicting a pictorial rendering of the acoustics operating like PanGeo Subsea Inc’s Acoustic Corer. Source: personal original sketch as produced for the patent, 2007

6.3 Forming a Large Wide Volumetric Acoustic Core

There are numerous sub-bottom profilers on the market that utilize well known and practiced art of synthetic aperture sonar, wherein independent of the acoustic signal generation and recording, there is an exacting and demanding continuous geodetic position requirement and orientation of the system for sub-bottom features to be coherently imaged on and to be constructively produced. This continuous motion is typically measured using a high-grade inertial navigation system (“INS”) whose clock is synchronized with that of the acoustics sensors.

The INS data are typically collected at the highest possible refresh rate, which typically ranges from 10 to 25 Hz. Without occasional input of absolute geodetic position information at selected time intervals, an INS system drifts during long term usage hence sonar profiling systems involving Synthetic Aperture Sonar architectures depend on and are fallible to their INS systems, which periodically or continuously require corrections for drift.

A future embodiment of the ASI could see the acquisition of a very large Acoustic Core answer product approaching 100m or greater diameter by morphing the ASI’s acoustic data collection onto a discrete sonar imaging towed apparatus that would sit in a stationary manner on the seabed during an acoustic scan. The use of an INS system may be advantages in capturing positional changes during the scanning. The concept is to have the acoustic scanning transmitters and receivers secured onto a carriage assembly mounted on an ROV, AUV or bottom crawler as shown in Figure 108.

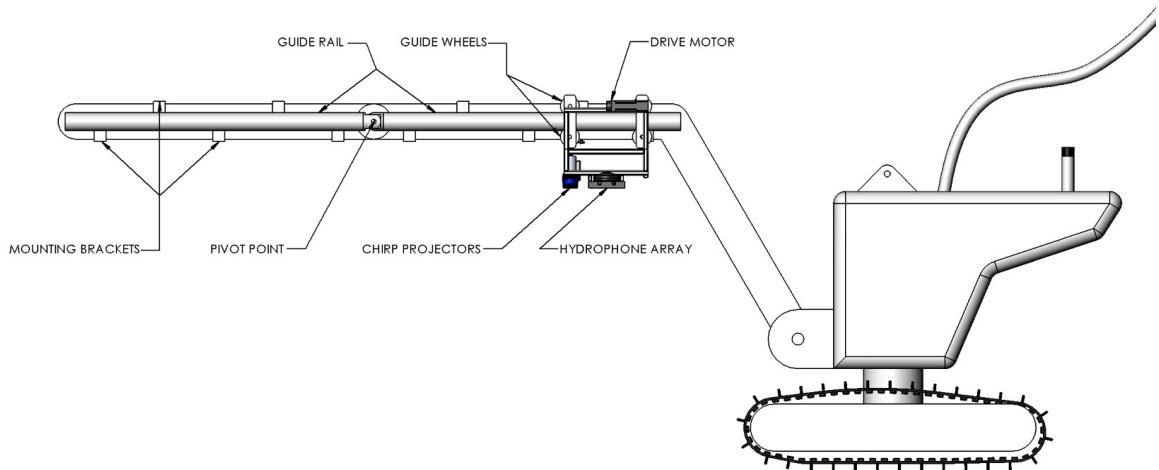


Figure 108: Application of a large volumetric mapping ASI which would rely on a “bottom crawling” vehicle or other remote ROV system typically used in offshore related work. The drawing is in support of the patent “Discrete Volumetric Sonar Method And Apparatus” by J.Y.Guigné, G.Dinn, A.Gogacz and N.G.Pace. Source: personal original sketch, drafted and produced by PanGeo Subsea in support of this new patent concept, 2012

For instance, a line array of acoustic receivers/transmitters could be mounted on the carriage assembly in a direction transverse to a direction of motion of the assembly. A position determining transponder would be attached on the carriage assembly. A plurality of position determining transponders would be disposed onto the seabed, with precisely located and known spaces.

The acquisition routines would be configured to communicate with the transponder mounted on the carriage assembly and with the units on the seabed. Basically, the imaging of sub-seabed formations would follow the ASI protocols that impart acoustic energy along a predetermined length swath at a selected geodetic position with accurate locations of all the sensors. Acoustic energy reflected from the formations would be detected along a line parallel to the length of the swath.

The carriage assembly after detecting signals at a known geodetic position would be moved a selected distance transverse to the length of the swath. The imparting of acoustic energy, detecting of acoustic energy and moving of the carriage assembly to a successive predefined geodetic position would be repeated until a selected distance transverse to the length of the swath is traversed.

The detected acoustic energy from all the selected geodetic positions is coherently stacked and is beam steered to each of a plurality of depths and positions along the length of the swath, stitched together to generate a large wide area image with such a depth and a position which ASI is designed to target, typically to 50m into the sub-seabed.

This approach would assemble four principal components:

- 1) a circular or other-shaped wire grid template or a highly accurate set of seabed positioning beacons, for example acoustic or optical beacons;
- 2) a carriage assembly which supports an x and y-axis translation of a broad beam, high-intensity acoustic transmitters with substantially co-located hydrophone receiver(s) along with associated supporting electronics, power supply, signal generators, data acquisition and signal storage, and conditioning and processing devices. The carriage may also

include a line array of hydrophones or similar acoustic receivers mounted thereon in a direction transverse to the direction of motion of the carriage during signal acquisition.

3) a pair of orthogonally oriented linear multi-channel receiver (e.g., hydrophone) arrays for placing directly on the seabed to achieve a highly folded JYG-Cross data collection; and

4) a bottom crawler ROV or other underwater remotely controllable vehicle to lift and accurately place the carriage assembly onto the water bottom through a virtually structured framework or onto the physical components of a mechanical/physical template.

Figure 109 illustrates the conceptual sonar carriage assembly.

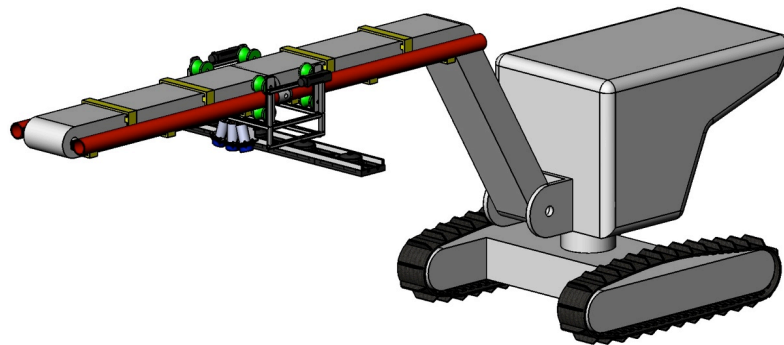


Figure 109: Application of a large volumetric mapping ASI which would rely on a bottom crawling vehicle or other ROV. The drawing is in support of the patent “Discrete Volumetric Sonar Method And Apparatus” by J.Y.Guigné, G.Dinn, A.Gogacz and N.G.Pace. Source: personal original sketch, drafted and produced by PanGeo Subsea in support of this new patent concept, 2012

Figure 110 illustrates the cellular imaging that would be obtained and how a continuously constructed or stitched, three-dimensional checkerboard operation could create cellular views of the sub-bottom as data is acquired. Such a cellular view would typically be 5 meters wide, 5 meters long and approximately 30 to 50 meters deep (into the seabed). By collecting these cells with centimeter positional knowledge the cells can be synthetically stitched together to form a large acoustic core footprint on the seabed.

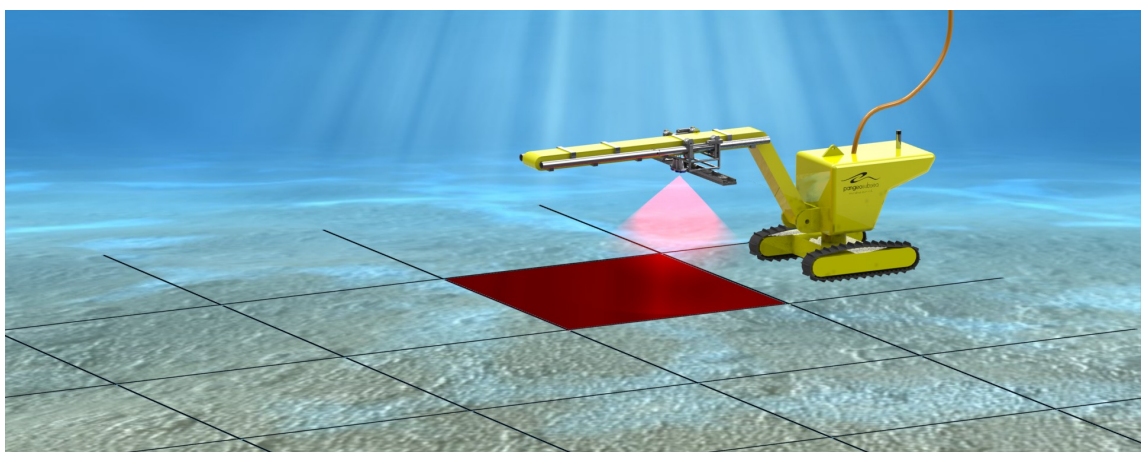


Figure 110: Application of an ASI through the creation of SAS cells stitched together precisely in checkerboard acquisition. The drawing is in support of the Discrete Volumetric Sonar Method And Apparatus patent by J.Y.Guigné, G.Dinn, A.Gogacz and N.G.Pace. Source: personal original sketch, drafted by PanGeo Subsea in support of the patent concept, 2012

The stable platform in the form of the carriage assembly enables deployment of sensors at a nominal 2 meters to 3.5 meters altitude above the water bottom. As a starting point, the broad-beam, high-intensity acoustic transmitter could comprise three, linear frequency modulation chirp projectors. The chirp projectors would be mounted on the carriage and oriented to form a swath of acoustic energy projected into the sub-bottom. The chirp projectors could each have 4.5-14.5 kHz bandwidth, and typically each chirp projector could provide a uniform 5-meter-wide swath of acoustic energy.

The sonar carriage would be held stationary during signal acquisition, and the position of the carriage would be determined and recorded before being moved to a new cell location along a selected direction of travel. After the carriage has been moved, signals are acquired and repeated. This procedure would be repeated until the carriage has moved along the entire length of the template or beacon pattern (a "line" of acquisition), and then moved a selected distance in an orthogonal direction. Acquisition may continue in the original direction of travel after orthogonal motion of the carriage. The orthogonal motion may be repeated after completion of each acquisition line until signal acquisition is obtained over the entire area defined by the template or beacon pattern.

The chirp projectors may be actuated in a sequence at a nominal rate of 75 Hz. A full swath may thus be realized at a nominal rate of 25 Hz. When a chirp projector emits its signal, data are recorded simultaneously on all hydrophones, in the line array, in a near vertical incidence receiver and in the two water bottom located orthogonal multi-channel linear receiver arrays. Some example embodiments may also include a novel chirp signal generation algorithm. Unlike general geophysical data acquisition and processing suites, the signal generation and processing parameters may be specifically selected for different water depth conditions, sub-seabed imaging of targets and so-called 'answer products. For a comprehensive and detailed description of the formation of the SAS cells, positioning interrogations and navigation protocols, and acoustical requirements to stitch the cells together, refer to Volume 3: Patents "Discrete Volumetric Sonar Method and Apparatus."

6.4 In Conclusion

The objective of the Guigné PhD thesis in 1986 was to introduce the concept for acoustic sub-seabed interrogations and to exhibit an acoustic core answer product by acquiring high frequency, specular and non-specular data with potential to unmask the internal textures and structures that make up a complex seabed. Having looked back at the past decades since the PhD thesis was examined in Bath, it is clear that the future in marine geotechnical investigations will incorporate more and more into its standards, the use of such acoustic answers and processes. A lot of the current work nevertheless rests on past pioneering acoustical studies with seabed. These studies helped establish an understanding of the challenges of correlating acoustics to geotechnical related properties; for example: Taylor Smith, 1974; Schultheis, 1980; Hamdi and Taylor Smith, 1982; Davies and Bennell, 1986; Taylor Smith, 1986; Guigné and Solomon, 1987; Clark and Guigné, 1988; Mayer et al., 1988).

Offshore site Investigations will continue to be characterized by exploration and by developments of marine-based petroleum reserves. What has changed to the activities that were reported in Guigné's 1986 PhD thesis is that, along with the oil explorations, vast wind farm projects have entered the scene worldwide and in a dominant manner. Unconventional petroleum and mining activities such as gas hydrates, heavy minerals and marine mining will also become important offshore resources, becoming commonplace and expanding in economic importance. It is almost certain that fuels from the Arctic and eastern northern offshore regions will be produced before the end of this decade. In later years, as the developments move from the continental shelf area to the

slopes, comprehensive marine geotechnical information will be required and depended on to mitigate installation risks.

The challenge to marine geotechnical engineers is to develop more cost-effective techniques of characterizing the soils upon which structures can be built on and through which boreholes will be drilled or from which minerals will be mined, and at the same time improve the quality of that characterization. The geotechnical engineer is involved in characterizing important environmental parameters. Practices in 2012 with respect to determining seabed loads, remains conservative with large margins to accommodate uncertainties and errors (personal exchanges with the marine geotechnical community in dealing with the marine engineering seabed stability issues faced for offshore wind farm foundation installations, 2010-2013). Such design loads issued for a structure, if vastly overestimated and if the foundation capacity is underestimated, the combined effects could lead to massive structures and foundations that are so expensive that it would be uneconomical to develop the reservoir or wind farm installation. Thus the influence of marine geotechniques is not limited to improving the economics of site characterization methods, although this is an important goal; it also has a direct input to the selection and design of the most appropriate structure from which to develop the field.

Since Guigné's thesis studies, advances have been made over the last decade in site characterization. The in situ methods, particularly the cone penetration tests described by Robertson (1986) and the self-bored pressuremeter tests by Jefferies et al. (1987) have improved significantly in their ability to determine the state of the soil and provide the property values required for design. Programs for curve fitting and interrogating into data will continue to evolve such that the engineer can have multi-faceted fused and cross-correlated data delivered in whatever form specified, whether it be state parameter, specific engineering properties, a pile design, or indeed an entire foundation design. The adoption and growth of ROVs, AUVs, and bottom crawler based marine robotics and vehicles suggest that it may soon be possible to do all of this remotely especially in exploring and developing resources in extreme environments. For example, geotechnical site investigations in the Arctic are being planned to be carried out by engineers using customized remote vehicles for surveying route selections, detecting, identifying, and removing geo-hazards and then safely burying cables systems (Dinn, 2012). Rapid 3-dimensional, volumetric site characterization and geo-hazard delineation will be essential for quality-controlled foundation designing without incurring cost prohibitive, conventional sampling programs.

The greatest cost of field investigations is the cost of vessel presently required for undisturbed soil sampling and in situ testing. Given the high costs of such vessels, effective in situ testing techniques instead of test borings can be a much more cost effective means of testing the soil, provided they give the information needed. The current trend is to lessen the reliance of drill holes and undisturbed samples to in situ tests with no samples, where the cost per meter of a cone test is typically about half that of a drilled hole.

The next obvious stage is to do what the present in situ tests accomplish by acoustically interrogating the seabed volumetrically, producing large diameter acoustic cores which could calibrate and intelligently direct the strategic placement of in situ tests and boreholes. The ASI's dynamic sound penetration and signal processing that Guigné described in 1986 and which PanGeo Subsea commercialized in 2010 has proven very adept in distinguishing layers, discontinuities, geo-hazards and fusing its data to geotechnical properties. If this methodology can be developed to the point where it will give the same information as can be obtained with present in situ methods, the economics of site investigation would dramatically improve by about two orders of magnitude.

The ASI imaging could by design be remotely controlled with pre-programmed self-navigating crawlers or specialized AUV's with little vessel dependency. The acoustic imaging science and supporting technologies are now in place and proven to deliver high resolution vertical and laterally at scales linked to the textural properties of the sediment, penetrating typically 50 m into the seabed with a final answer product, in theory reaching over a 100 m diameter acoustic core as an example. The cost would be measured in hundreds of dollars per meter, rather than thousands of dollars as is the present case.

The key is to produce an integrated approach to site investigations on a very large scale which would see an ASI imaging methodology be applied off a crawling robotic technology that could create discrete volumetric cells of acoustic data with in situ tests conducted intelligently off the same platform, co-located within a checkerboard type of data acquisition. Then after completing a wide areal map (say, 1km² with 50 meter detailed depth sub-seabed interrogations and in situ probing), the ASI cells (with the in situ tests) would be processed off of a large data processing cluster made up of CPUs and GPUs forming a dedicated computer farm. The rendered data would be transported and visualized as a fused geoscience database accessed through a GIS integrated adaptive geotechnical engineering computer aided design exchange. For example, an offshore route for burial of pipelines or cables, or a marine installation site could be accessed through this smart database and details specific to a project would be revealed with data confidence at scales that would mirror the geotechnical requirements and variability and spatial distributions of the characterizing soil properties, anomalies and geo-hazards. This is achievable today and should be the focus for marine geotechnical engineering investigations of complex seabeds.

The use of remote sensing approaches relies on correlations with interrelationships with cone penetration tests and self-bore pressuremeter tests such as originally described by Been et al. (1985) and Jefferies et al. (1987). Continuing research in the constitutive relationships between engineering properties and the physical nature of soils could provide the guidelines to establish new test standards and will contribute to the elimination of unreliable empirical correlations (personal communications with the Norwegian Geotechnical Institute, 2012).

Trends are now seen in the application of expert systems to site characterization and design, such as automatic curve fitting methods for conventional in situ tests, innovative methods of interrogating the seabed by acoustics, and real-time graphic parallel processors that can produce answers quickly to engineering decisions that affect the economics and safety of offshore operations. Stuyts (2010) introduced the use of geo-statistics to help eliminate the need for a borehole at every wind farm foundation given that the input into the statistics carries spatial information of the substrata boundaries in a reliable, representative manner. This trend will reduce the requirement to look at a soil or touch it or break it or shake it. That will all be done indirectly. Design alternatives will be provided that could be economically predicted and conceptually constructed and optimized through expert computer aided design software to eliminate decision biases and subjective judgments on the part of the installation engineer.

Just as it was in 1986 when the author suggested in his PhD defense the concept for an acoustic core product through acoustic interrogations of the seabed, so it is decades later that geotechnical engineers, marine geologists, and marine geophysicists, whether they are involved with the design process or regulatory process, will still want to see the soil they are dealing with and will want to test it in their laboratories to guide them in exercising their best judgment on how best to design, build, or regulate a development. But site investigation methods are changing, with more complete and reliable imagery of the distribution of soil textures, structures, and hazards. More ASI based remote sensing will diminish the number of physical cores taken and will provide better understanding of

the scaled significance and reliability of fused datasets with acoustics. This will provide for more complete pictures with less sampling and laboratory testing. There will continue to be increased usages of robotics and expert systems to enhance the present-day in situ testing methods. The future for acoustic interrogating complex seabeds will without doubt become most interesting and important in the years to come.

References Cited

Been K. & Jefferies M.G. (1985). A state parameter for sands. *Geotechnique* (35), 99-112.

Clark J. I. & Guigné J. Y. (1988). Twenty-fifth anniversary special paper: Marine geotechnical engineering in Canada. *Canadian Geotechnical Journal*, 25, 179-198.

Davies A. & Bennell J. D. (1986). Dynamic properties of marine sediments. In Ocean-seismo acoustics. (Aka1, T. & Bernson, J.M., eds.) New York, NY: Plenum Publishing Corporation.

Dinn G. (2012). Field experience with a new sub-bottom investigation tool: Acoustic 3-D imaging of the sub-seabed. *Oceans 2012*, proceedings

Guigné J. Y. (1986). *The concept, design and experimental evaluation of 'acoustic sub-seabed interrogation.'* Ph.D. thesis, University of Bath, Bath, England.

Guigné, J.Y. & Solomon, S. (1987). *Correlation of acoustic and geotechnical properties of uniform saturated silica sands using acoustic sub-seabed interrogator technology.* Centre for Cold Ocean Resources Engineering, St. John's, Nfld., C-CORE Report 87-10.

Hamdi, F. & Taylor Smith, D. (1982). The influence of permeability on compressional wave velocity in marine sediments. *Geophysical Prospecting*, 30, 622 -640.

Jefferies M.G., Crooks, J.H.A., Becker, D.E., & Hill, P. R. (1987). Independence of geostatic stress from over-consolidation in some Beaufort Sea clays. *Canadian Geotechnical Journal*, 24, pp. 342-356.

Schultheis P. (1980). Simultaneous measurement of P and S wave velocities during conventional laboratory soil testing procedures. *Marine Geotechnology*. (4)4, 343-367.

Taylor Smith D. (1974). Acoustic waves in saturated sediments *In* Physics of sound in marine sediments. (Hampton, L., ed). New York, NY: Plenum Publishing Corporation.

Taylor Smith D. (1986). Geotechnical characteristics of the seabed related to seismo-acoustics *In* "Ocean-seismo acoustics" (T., Aka & J. M., Bernson, eds.) New York, NY: Plenum Publishing Corporation.

Mayer, L., Moran K., Piper, D. J., & Courtney, R.C. (1988). Long cores from Emerald Basin, Nova Scotia: physical, and acoustic properties. *Geological Survey of Canada Fomm*, Ottawa, Ont.

Robertson, P.K. (1986). In situ testing and its implication to foundation engineering. *Canadian Geotechnical Journal* (23), pp. 573-594.

Stuyts, B. Vissers, V, Cathie, D. N. (Cathie Associates), Dorfeldt, S. (Offshore Wind Technology), (2010). Optimizing Site Investigations and Pile Design for Wind Farms Using Geostatistical Methods: A case study. *Frontiers in Offshore Geotechnics*, Perth

Australia, 8-10; ISFOG II.

Volume 2 – Associated And Related Patents/Publications By The Author

Guigné, J.Y. (2010) *US Patent No. 7,715,274 B2*. USA Patent Office.

Guigné, J.Y., Dinn, G., Gogacz, A., & Pace, N.G. (2012). US Patent Application - Discrete Volumetric Sonar Method And Apparatus For Sub-Seabed Surveying